Jet Noise Predictions with Wall-Modeled Large Eddy Simulations

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*Science And Technology Corporation (STC)

Outline

- **WHY** do we investigate Jet noise ?
- **WHAT** are the challenges for jet noise predictions with WMLES ?
- **HOW** do we solve these challenges – Numerical Method?

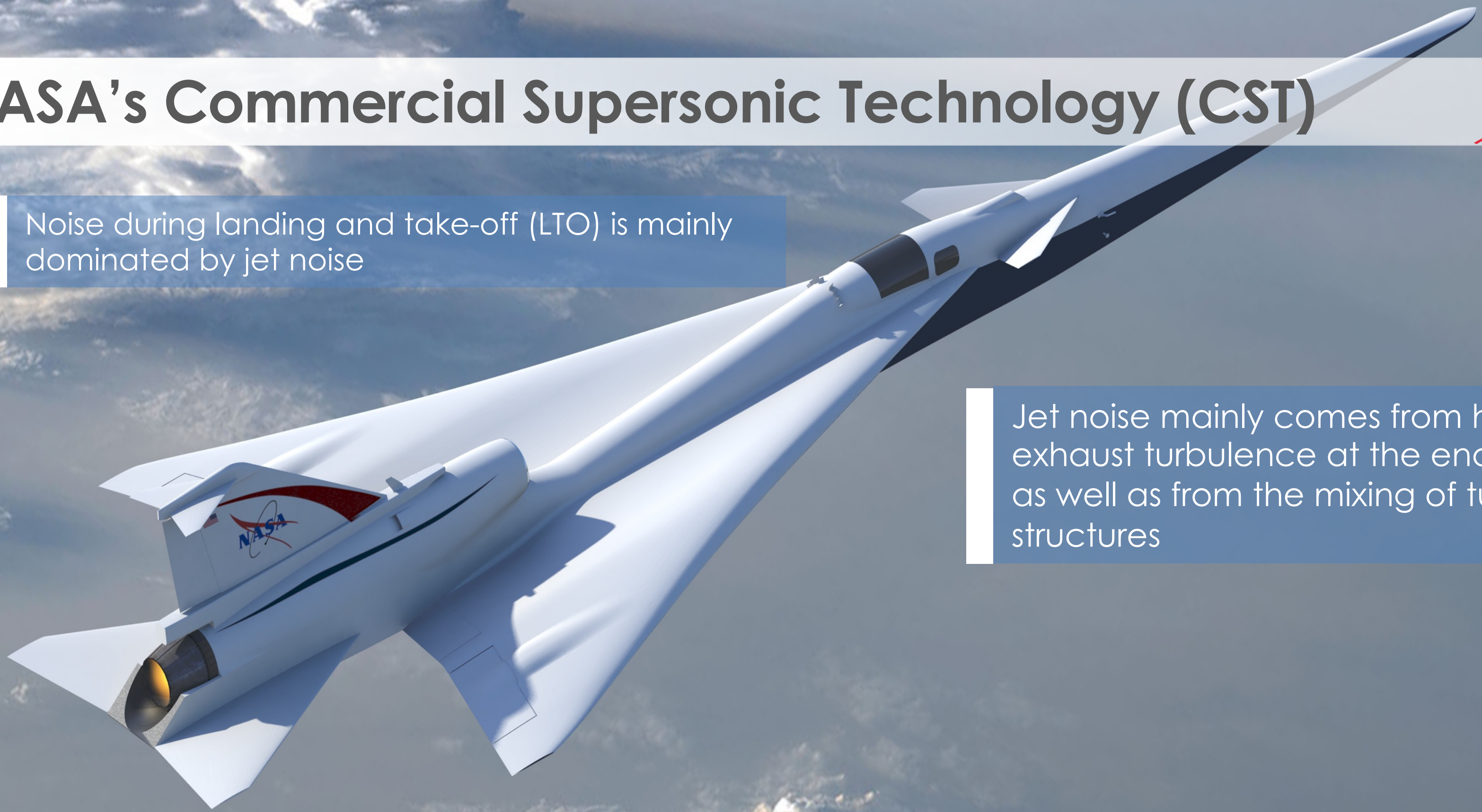
- **PART I:** Evolution of jet noise research within LAVA
  - *Steps to predict jet noise for full-scale aircraft configuration*
- **PART II:** Prediction Uncertainty Reduction (PUR)
  - *Increase confidence in quality of jet noise predictions*
    Stich et. al. (AIAA SciTech 2022-0648)

- **Summary and future directions**

NASA's Commercial Supersonic Technology (CST)

Noise during landing and take-off (LTO) is mainly dominated by jet noise

Jet noise mainly comes from high-speed exhaust turbulence at the end of the nozzle as well as from the mixing of turbulent structures



NASA supports ongoing research activities towards commercial Supersonic Technologies (CST)

Picture Credit: NASA / Lockheed Martin

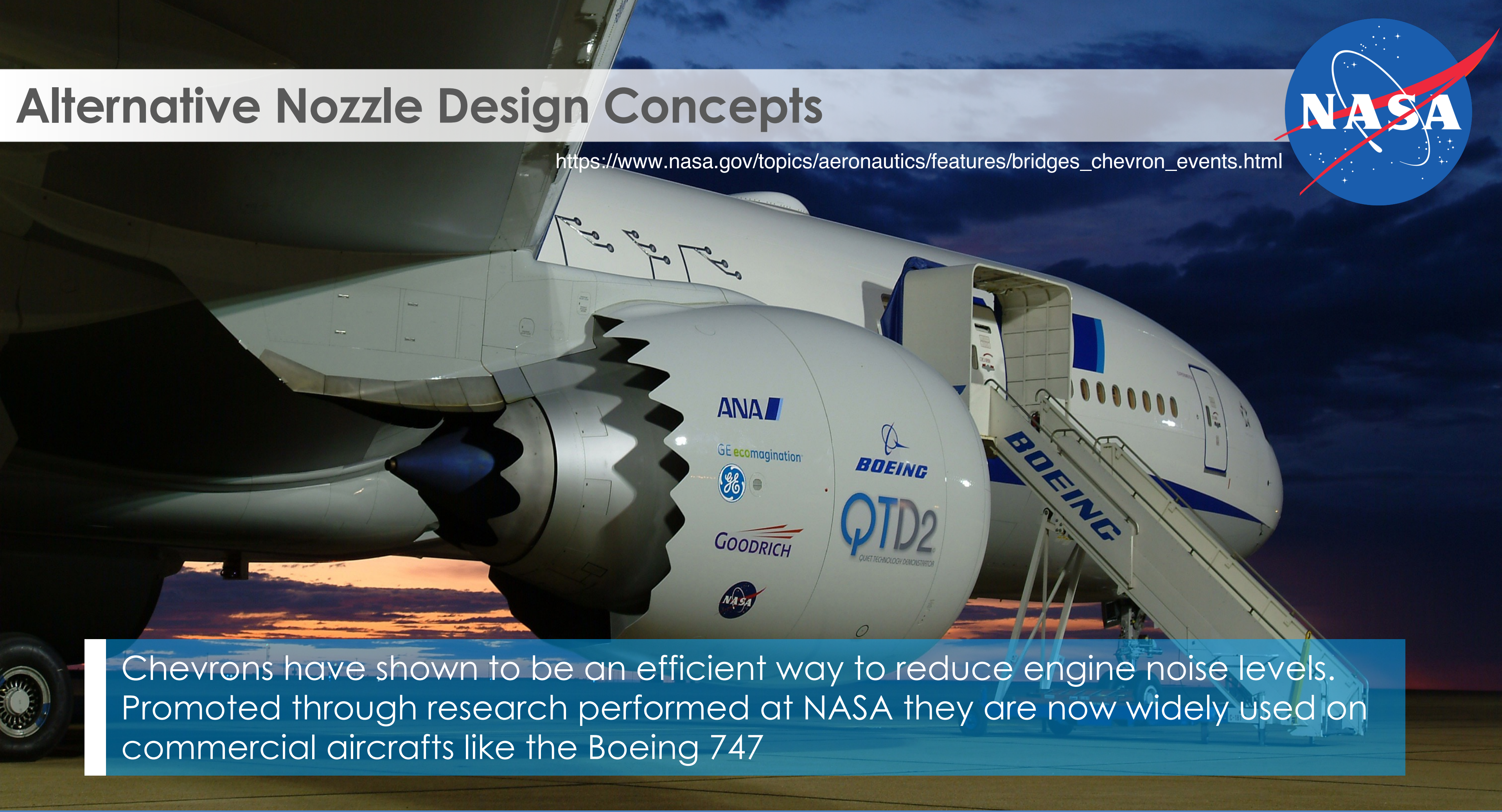
https://www.nasa.gov/sites/default/files/thumbnails/image/16-022-supersoniccontract.jpg

Integrated Propulsion Noise

Integrated propulsion noise or jet surface Interaction noise (JSI) becomes increasingly more important with future aircraft designs

Alternative Nozzle Design Concepts

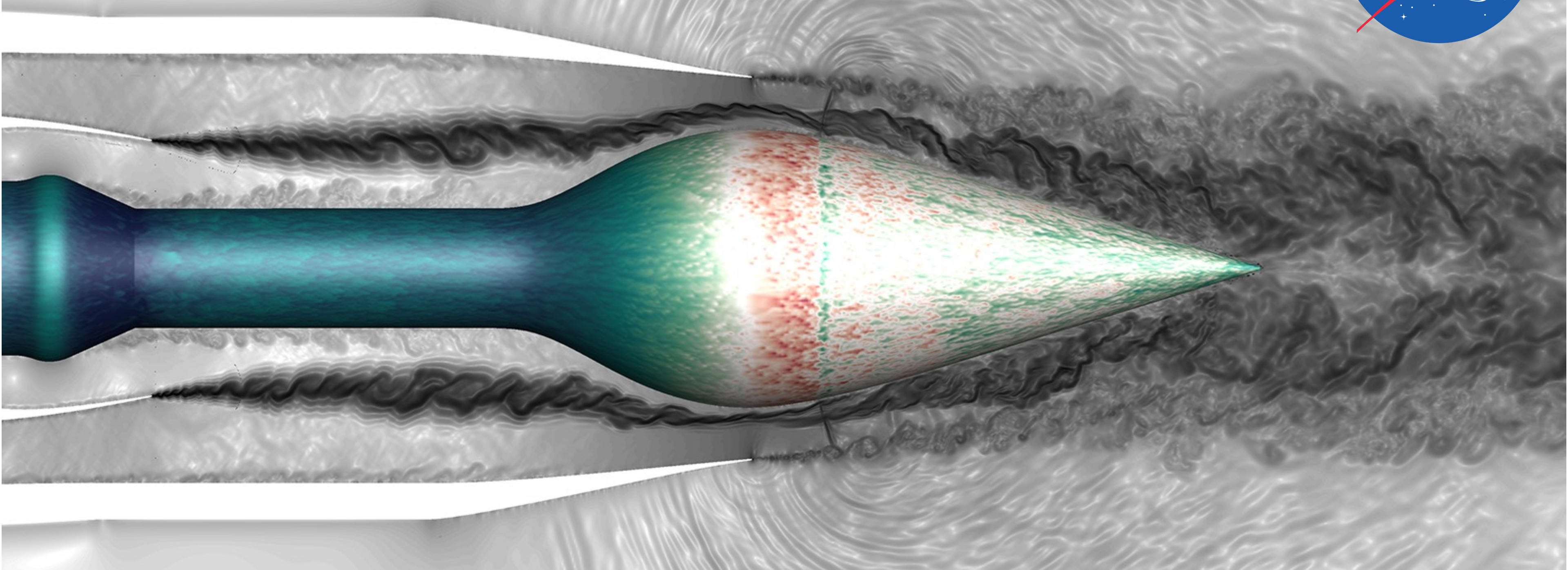
https://www.nasa.gov/topics/aeronautics/features/bridges_chevron_events.html



Chevrons have shown to be an efficient way to reduce engine noise levels. Promoted through research performed at NASA they are now widely used on commercial aircrafts like the Boeing 747

Role of Computational Aeroacoustics (CAA)

High-fidelity scale resolving simulations conducted at NASA's CST Project under the direction of James Bridges accurately capture physics of turbulence creating noise.



Determining where and how noise is created could help reduce overall jet engine noise. Accurate predictions of jet noise can help shape future FAA guidelines for supersonic vehicles

<u>WHAT</u>
are the challenges ?

Jet Noise Simulation – Challenges of Physical and Numerical Modeling

- Nozzle and operating conditions (nozzle pressure ratio NPR, Mach number, …)
- Nozzle exit boundary layer state (turbulent, laminar)
- Entrainment and co-flow
- Installation effects

- Spatial and temporal resolution
- Correct sub-filter scale modeling
- Boundary condition treatment (resolved, modeled)
- Far-field acoustic predictions
- Managing data storage and i/o efficiently

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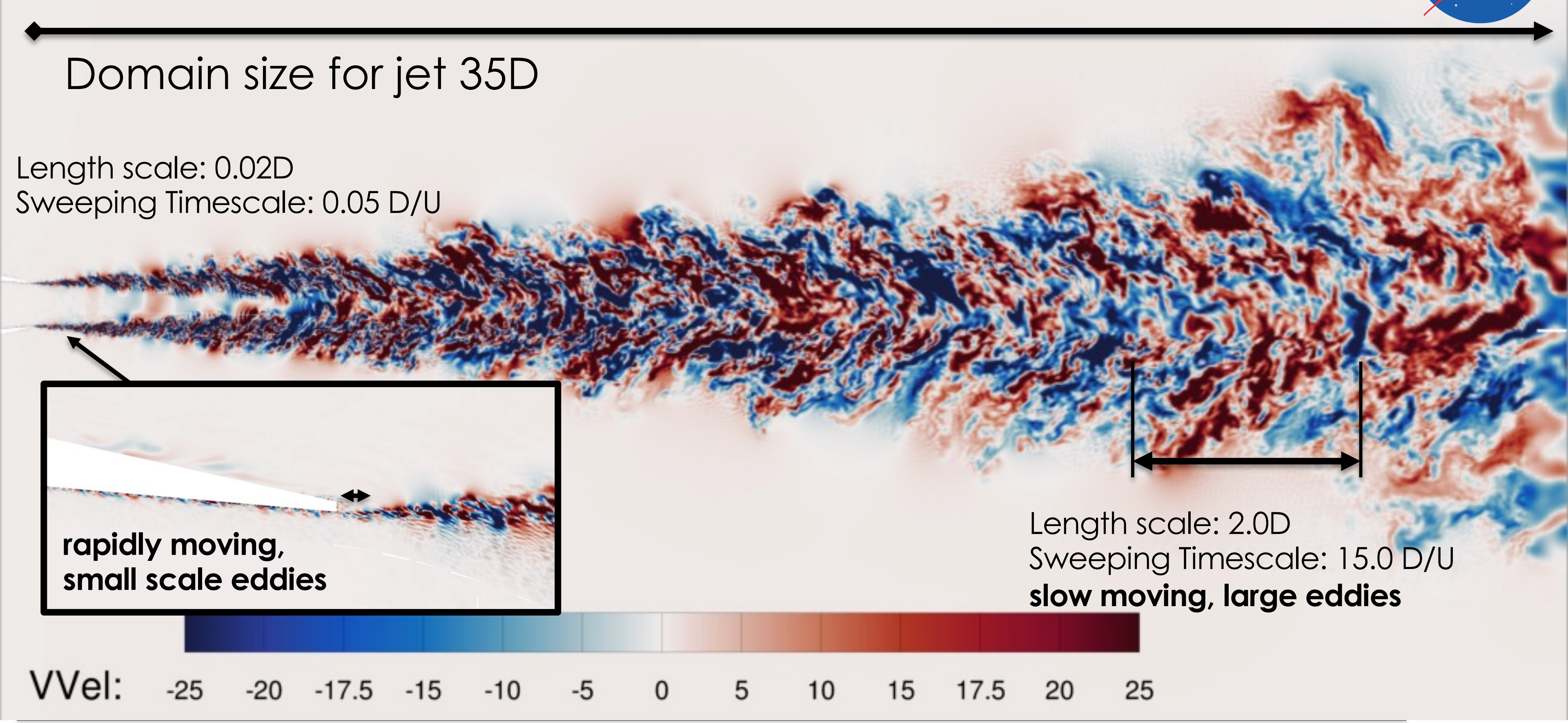
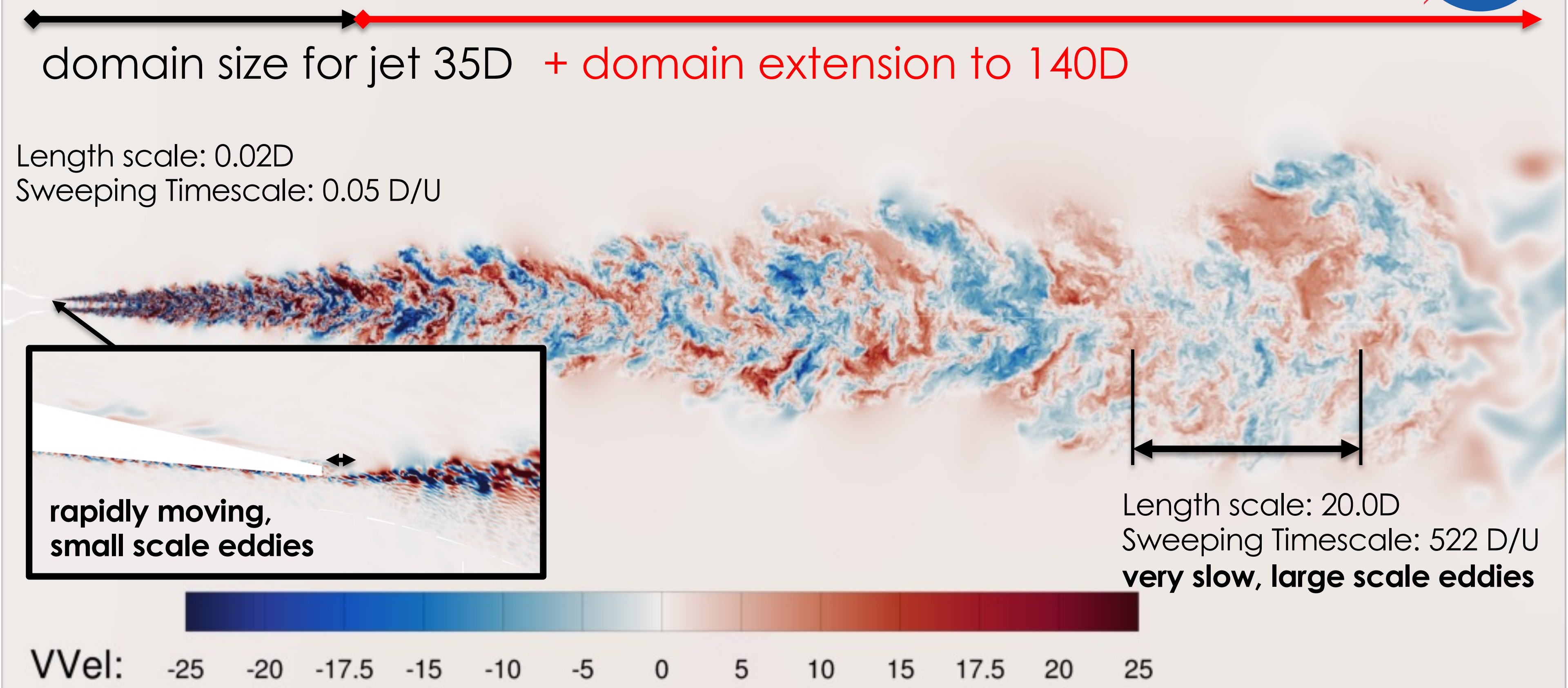
Why are Scale-Resolving Jet Noise Simulations Expensive?



Why are Scale-Resolving Jet Noise Simulations Expensive?



Why are Scale-Resolving Jet Noise Simulations Expensive?

CHALLENGE

SIMULATIONS NEED TO RUN WITH A SMALL ENOUGH TIME-STEP (FAST STRUCTURES) **FOR A LONG SAMPLE TIME** (SLOW STRUCTURES)

(EXPENSIVE LONG SIMULATION)

CPU SCALING LIMITATIONS

ADDING MORE COMPUTE POWER WILL NOT REDUCE THE OVERALL SIMULATION TIME

(LIMIT OF POINTS PER CORE)

EXTREMELY EFFICIENT TOOLS

HAVING AN EXTREMELY EFFICIENT SOLVER AT PEAK PERFORMANCE AND OPTIMAL NUMERICS IS CRUCIAL (WEAK & STRONG SCALING)

<u>HOW</u>
do we solve these challenges?

The Launch, Ascent and Vehicle Aerodynamics (LAVA) framework

Objectives within NASA's CST project for Jet Noise

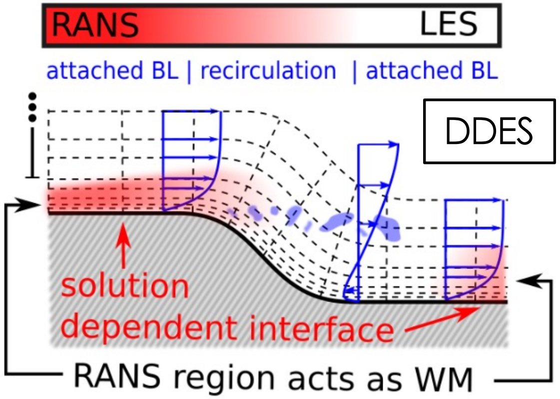
- Predict jet noise **accurately** and in **short enough turnaround time** using **scale-resolving** simulations methods
- **Understand** and document **uncertainties and shortcomings** of scale-resolving wall-modeled LES for jet noise simulations
- **Future Impact:** complement/replace wind tunnel and flight tests, reduction of associated costs, provides insight into noise reduction technology never-before available.

Kiris et. al. Computational framework for Launch, Ascent, and Vehicle Aerydynamics (LAVA) (2016)

Hybrid-RANS/LES (HRLES) for jet noise

Basic philosophy:

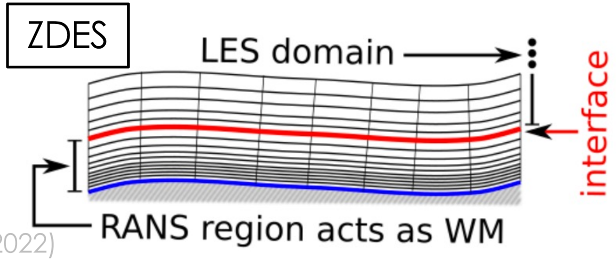
Use RANS in near-wall region and quickly transition towards LES in free-shear layers and acoustic source regions.



- Classical HRLES like DDES rely on robust "indicator function" which informs switch to LES
- Zonal HRLES methods use a prescribed interface to switch to LES

Zonal HRLES for jet noise: ZDES Mode III by Deck et al.

- Utilize RANS only in near-wall region up to defined interface height
- Required $y^+ = 1$ mesh in BL is expensive and localizes points near geometry
- Results in highly skewed large aspect ratio cells which are problematic for LES and acoustics



*HRLES in LAVA: Housman et al. (2016, 2017), Stich et al. (2018, 2019), Ghate et al. (2020, 2021, 2022)

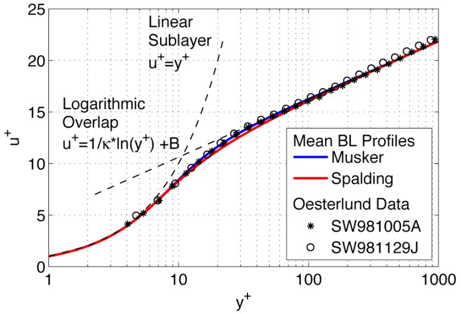
Stress Based Wall-Modeled Large-Eddy Simulation (WMLES)

Basic philosophy:

Would like to use LES everywhere but cannot resolve integral length scales for the inner-layer of a turbulent boundary layer at high Reynolds number; replace stiff-Dirichlet BCs with a wall-stress BC instead and compute the wall-stress using a wall function.

In this work analytical law of the wall

- Utilize wall functions (e.g. Musker's Law) and compute wall shear-stress based on velocity from LES
- Computationally simple and inexpensive

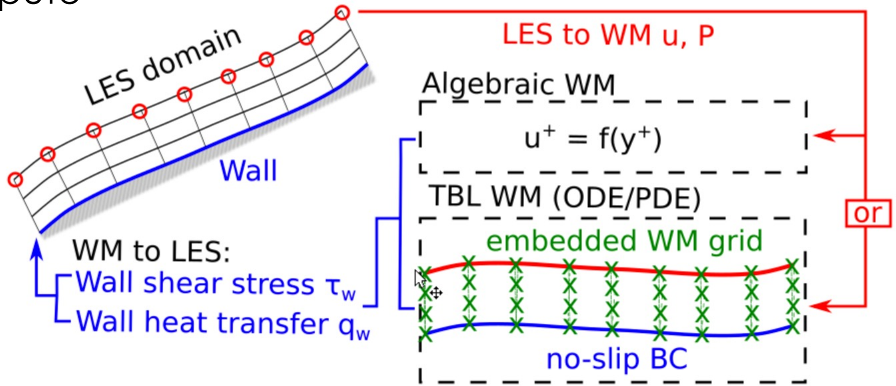


ODE based WM

$$\boxed{\frac{d}{dy}\left[(\nu+\nu_t(y))\,\frac{du}{dy}\right]=0}$$

Algebraic WM

$$\boxed{u^+ = f(y^+)}$$



*Recent reviews of WMLES by Larsson et al. (2016) or Bose & Park (2018)

A Brief Overview of Jet Noise Predictions with LES

- **Early LES simulations of jets before 2008 made pragmatic compromises**
  - *Nozzle geometry not modeled e.g. Shur (2005, 2006)*
  - *Reduced Reynolds number between 0.1 to $5x10^5$ e.g. Bodony (2005), Uzun (2004)*
  - Review paper summarizing early LES jet simulations Bodony & Lele (2008)
- LES at flight Reynolds number, slip + synthetic turbulence Bres (2012) Pauz (2017)
- **Establishing the importance of getting the BL state right**
  - Turbulent boundary layer inside of nozzle Bres (2015, 2018)
  - Inflow turbulence on jet noise Bogey (2010,2012)
- 2009-present: various hybrid RANS/LES simulations including nozzle with $y^+ < 1$ Xia (2009), Engel (2014), Wang (2017), Housman (2017)
- **Inclusion of alternative nozzle designs**
  - Chevron nozzle simulations Uzun (2012), Stich (2021)
  - Jet surface interaction noise Stich (2019), Mocket (2020)
- **Wall-modeled LES at full Reynolds number of round jet $y^+ > 1$** Bres (2018), Stich (2021,2022), Wu (2021), Bogey (2021)
- Review paper of state-of the art LES jet simulations until 2019 (Bres & Lele 2019)

PART I
Evolution of Jet Noise Research within LAVA

Housman et. al. (AIAA 2017-3123)
Stich et. al. (AIAA 2019-2475)
Stich et. al. (AIAA 2021-1185)

2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets

ROUND JET VALIDATION

1

SHIELDING CONCEPTS

2

INCREASINGLY COMPLEX GEOMETRY
(Chevron, Plug, Multi-stream)

3

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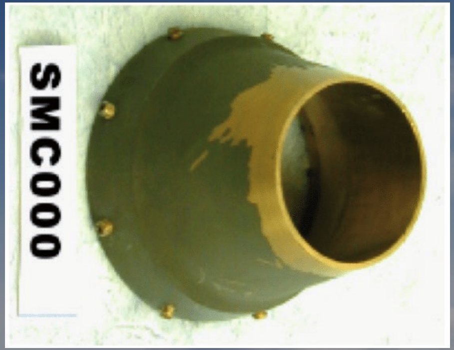
ROUND JET VALIDATION

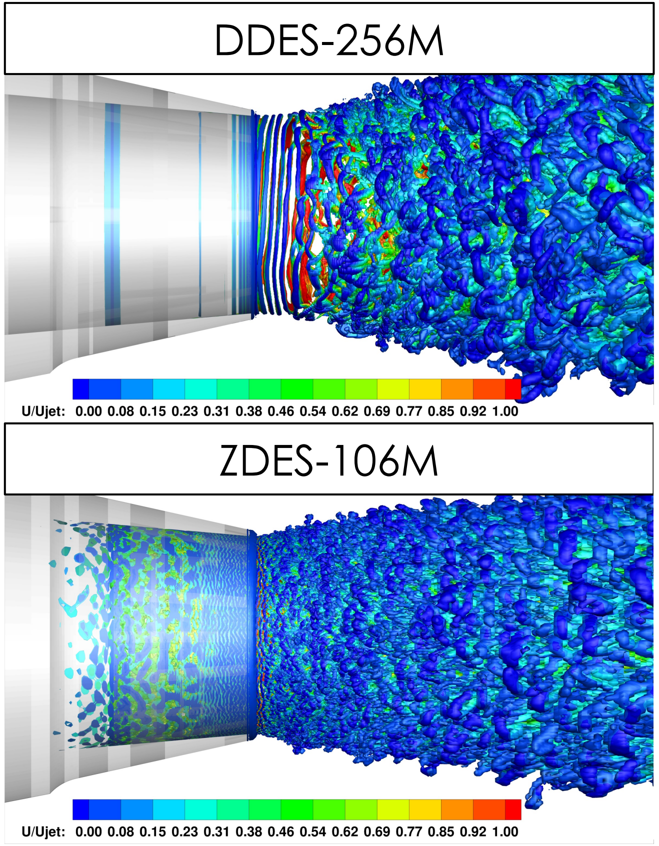
1

1. **Hybrid RANS/LES 2017**

- Detached Delayed Eddy Simulation
- Zonal Hybrid RANS LES
- Part of NASA vision 2030 RCA challenge

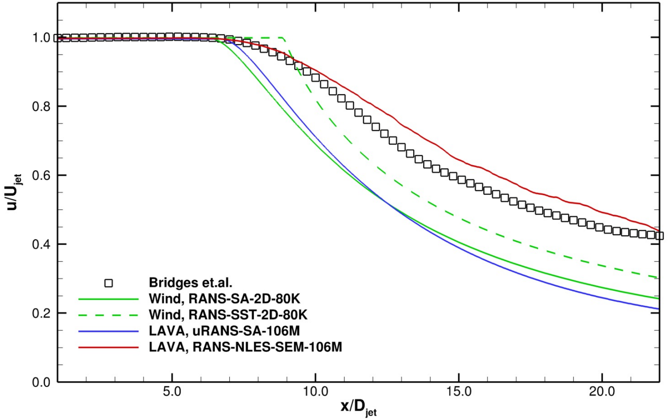


2017: Round Jet Validation - Hybrid RANS/LES



NASA RCA has introduced challenge for jet noise

- Improve Simulation accuracy by 40%
- Prediction of length of potential core ($U/U_j = 0.98$)
- Improvement of centerline TKE Prediction
- See Housman et. al. (AIAA-2017-3213)



89.6% improvement

solver	Error [%]
Bridges & Wernet Exp.	-
State-of-the-Art SA-RANS[1]	-12.3
LAVA Hybrid RANS/LES	**1.2**

[1] RANS Data, Objectives and Metrics from NASA Turbulence Modeling Resource (TMR) website

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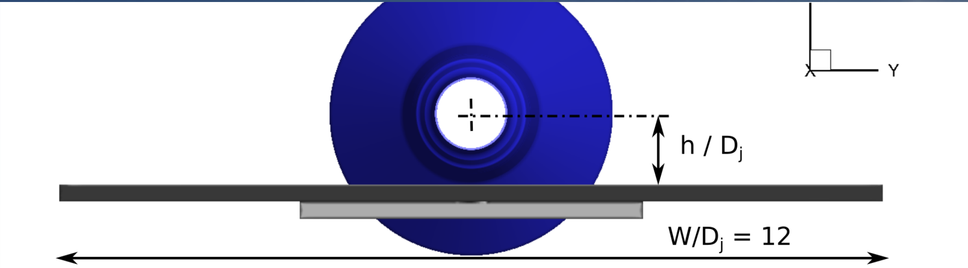
SHIELDING CONCEPTS

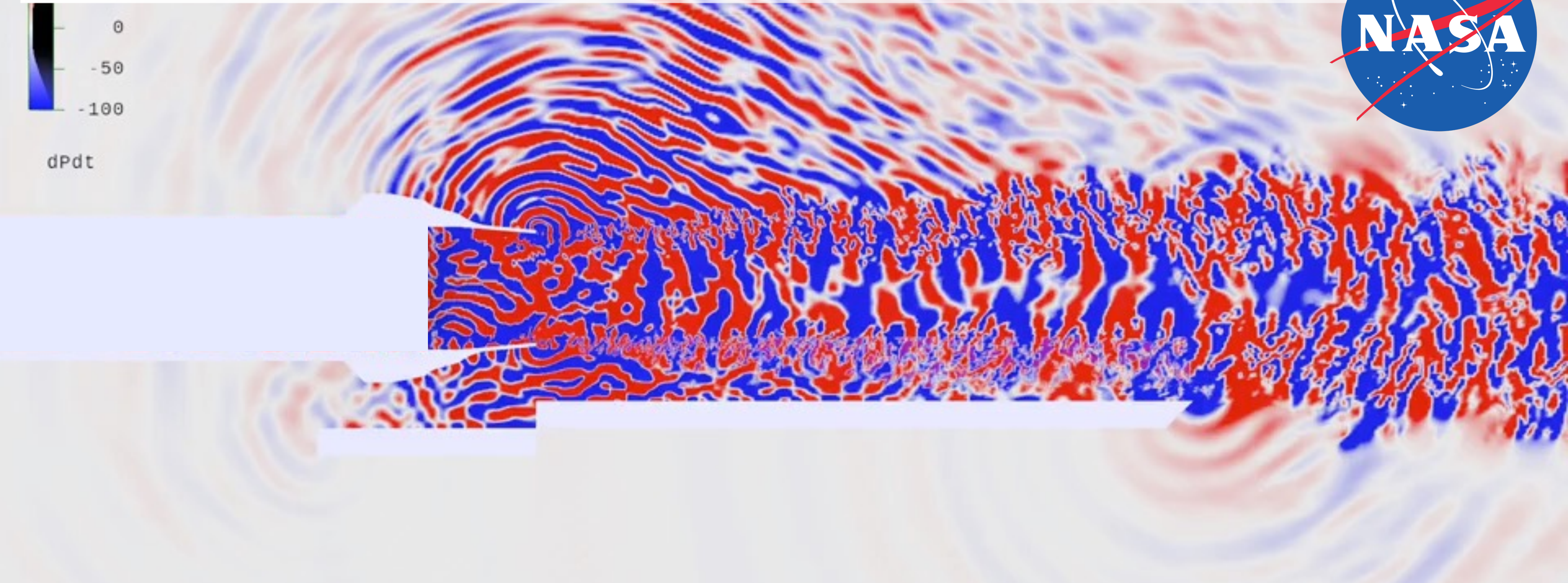
2

Hybrid RANS/LES of jet-surface interaction noise

- **Same round jet configuration utilized with plate mounted underneath**



2019: Jet Surface Interaction Noise – Jet in Proximity to Surface



Stich et. al. (AIAA2019-2475): Large-Eddy Simulation of Jet Surface Interaction Noise

Determining where and how noise is created and how noise can be "shielded" from the observer could help reduce overall jet engine noise.

Flow Visualization by Timothy Sandstrom NASA Ames Research Center

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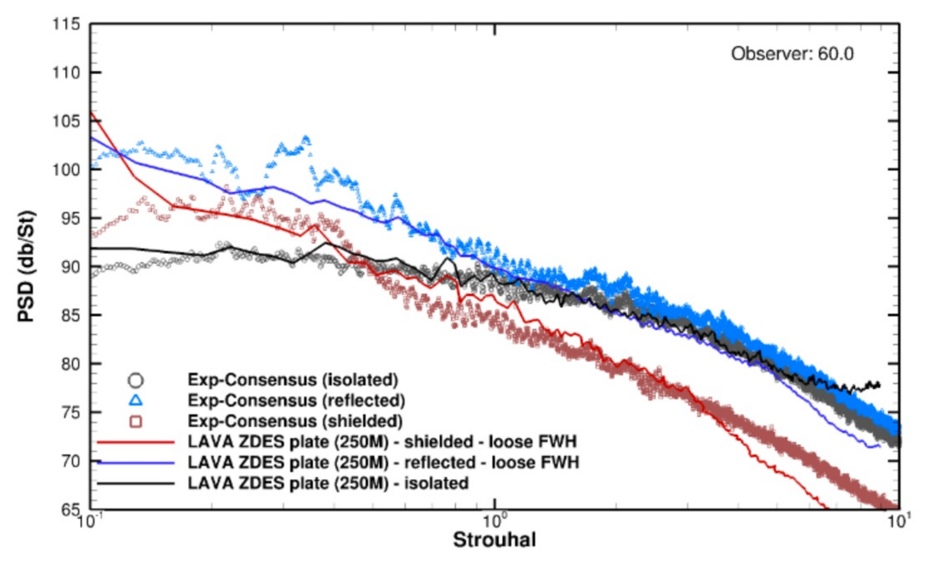

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INCREASINGLY COMPLEX GEOMETRY
(Chevron, Plug, Multi-stream)

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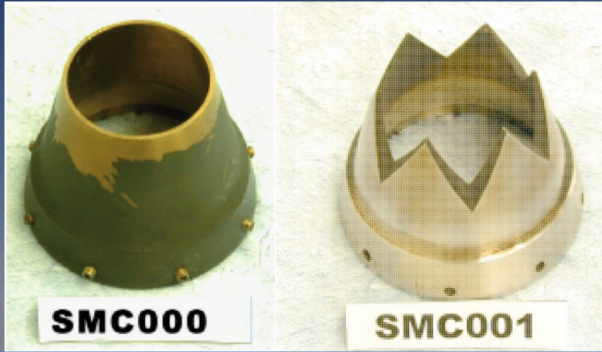
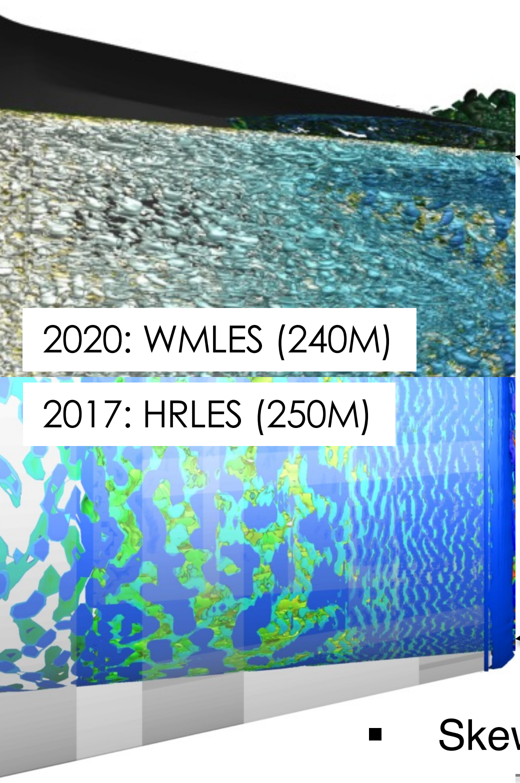
- Development of wall-modeled LES (LES) capability funded by NASA TTT within LAVA solver Framework

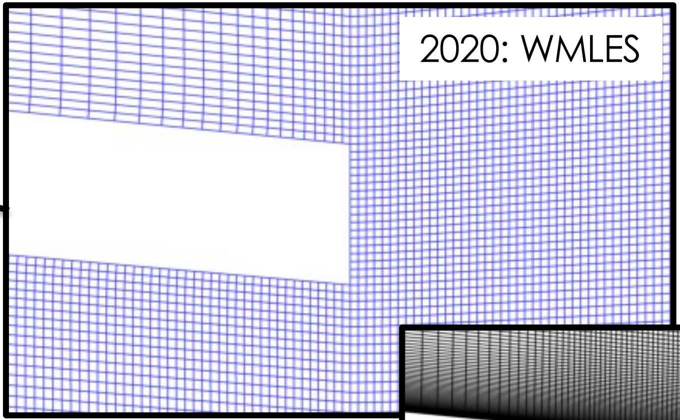
Comparison of chevron nozzle with round jet



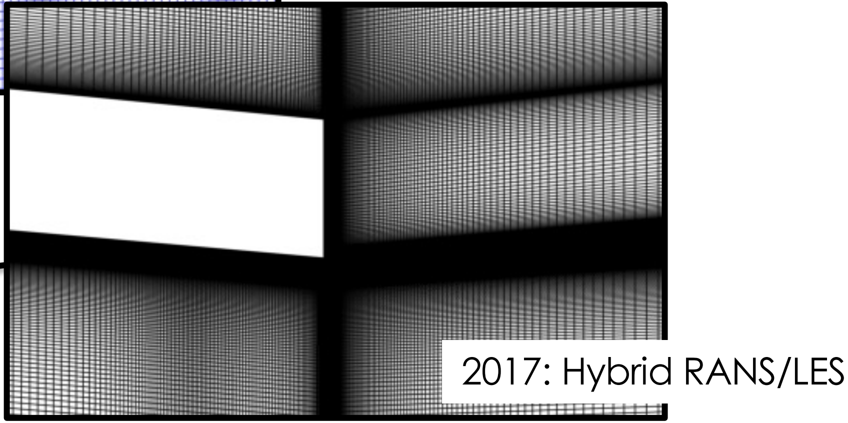
2020: Utilization of Wall-Modeled LES (WMLES)

- Points from resolving near-wall gradients distributed throughout the domain
- Improved aspect ratio (AR) allows ”better” numerical treatment (less dissipation)





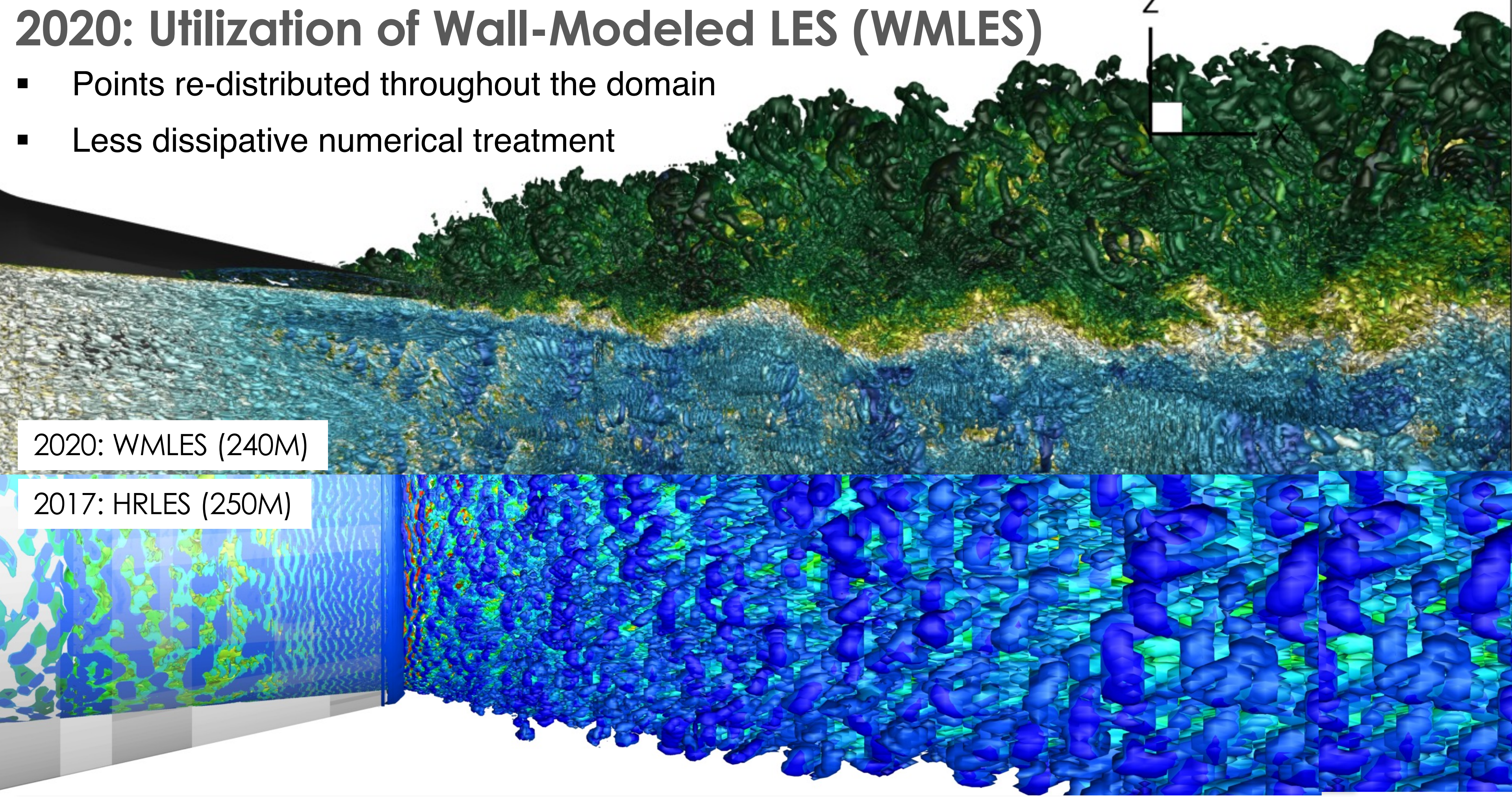
- Aspect ratio 1 cells



- Skewed high aspect ratio cells

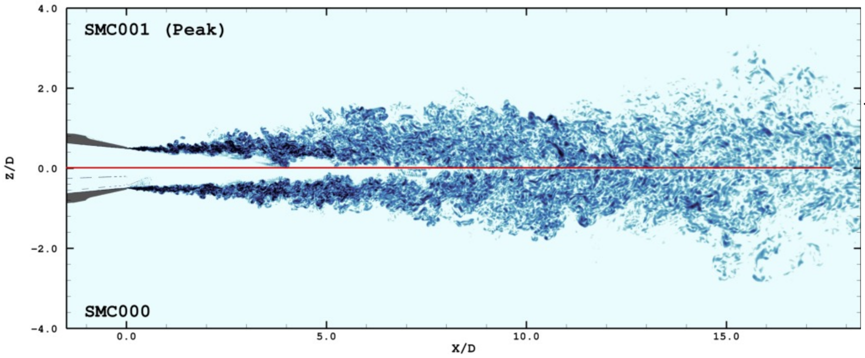
2020: Utilization of Wall-Modeled LES (WMLES)

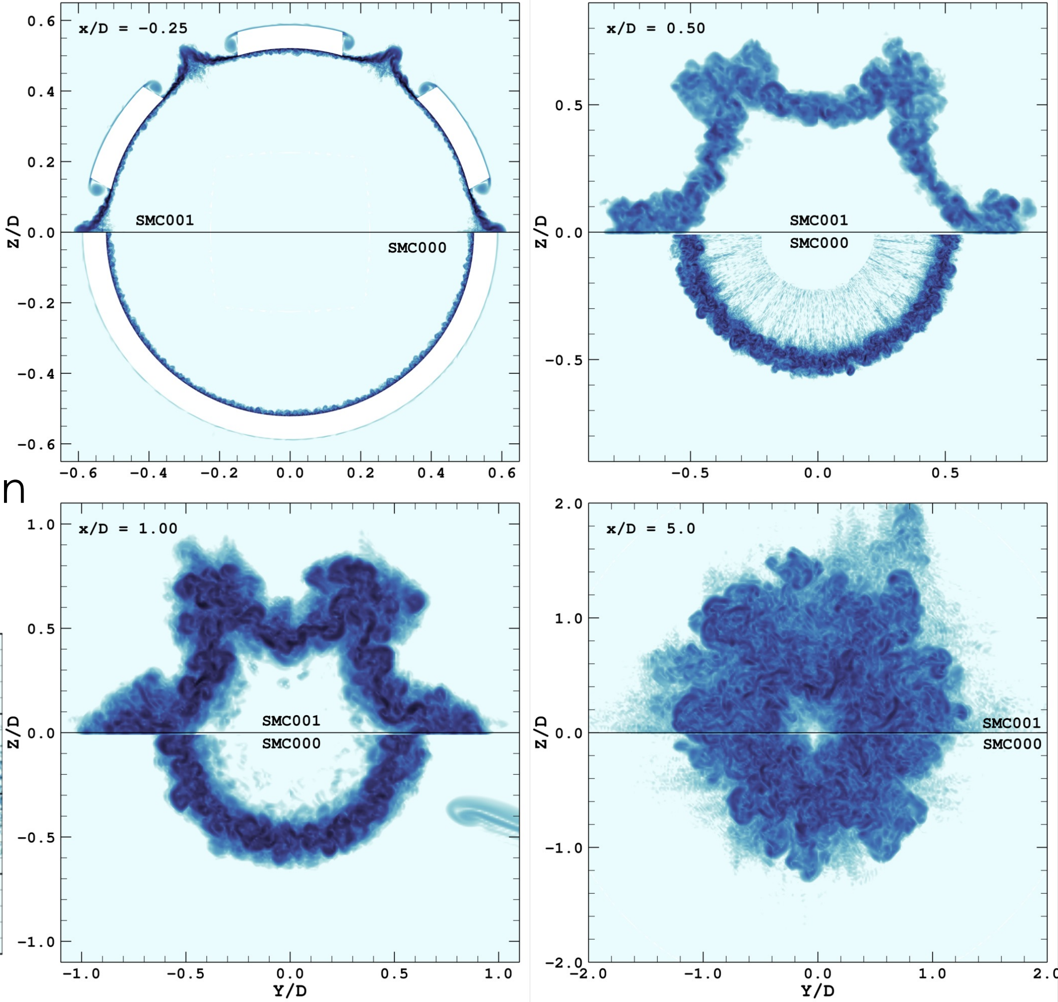
- Points re-distributed throughout the domain
- Less dissipative numerical treatment



Flow Field Comparison
Chevron vs Round Jet

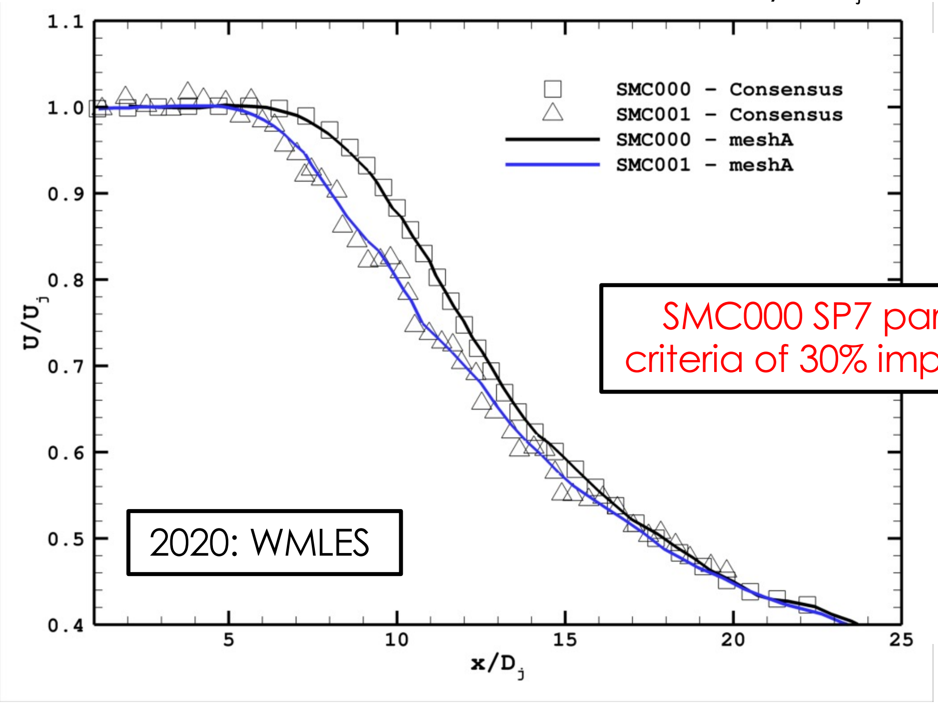
- Vorticity magnitude for chevron nozzle (top) round-jet (bottom)
- Stronger jet spreading in chevron compared to round jet
- Vorticity roll-up at nozzle exit at chevron
- Stich et. al. (AIAA-2021-1185)





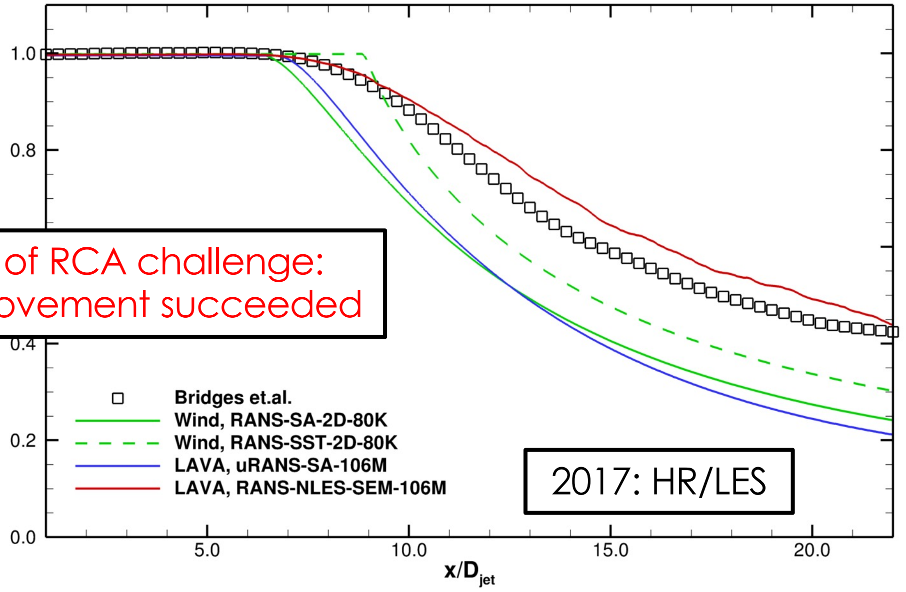
Near-Field Comparison: Centerline

dimensionless streamwise velocity u/U_j



SMC000 SP7 part of RCA challenge: criteria of 30% improvement succeeded

NASA RCA (Vision2030) Improvements in Jet Predictions

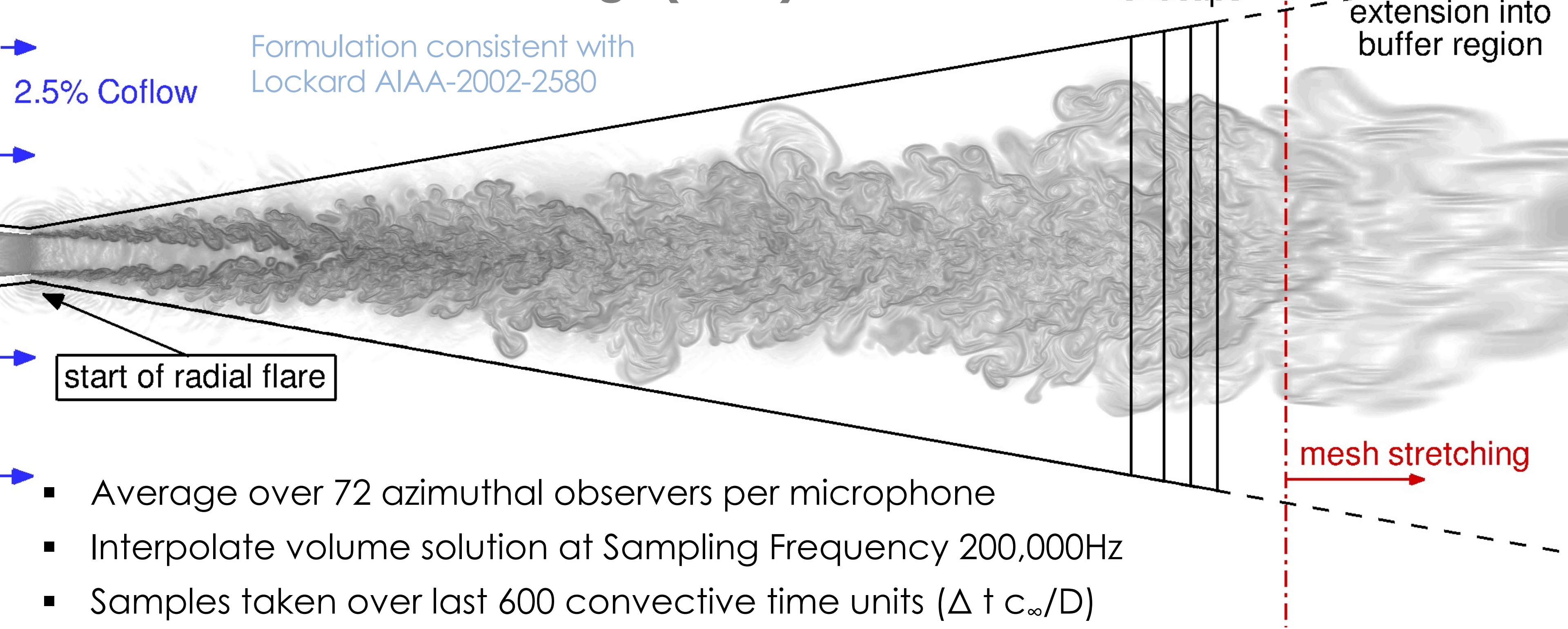


- Length of potential core predicted accurately (U/U_j = 0.98)
- Location and magnitude of normal stress agrees well with experiment

SMC000: Round
SMC001: Chevron

Ffowcs Williams-Hawkings (FWH)

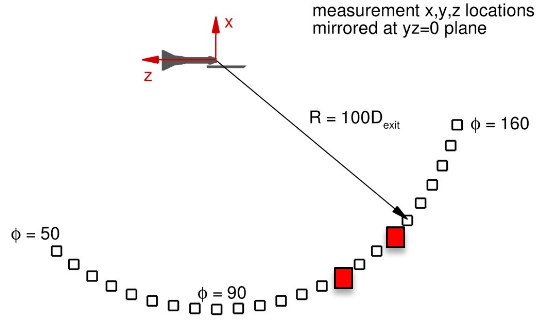
Formulation consistent with
Lockard AIAA-2002-2580

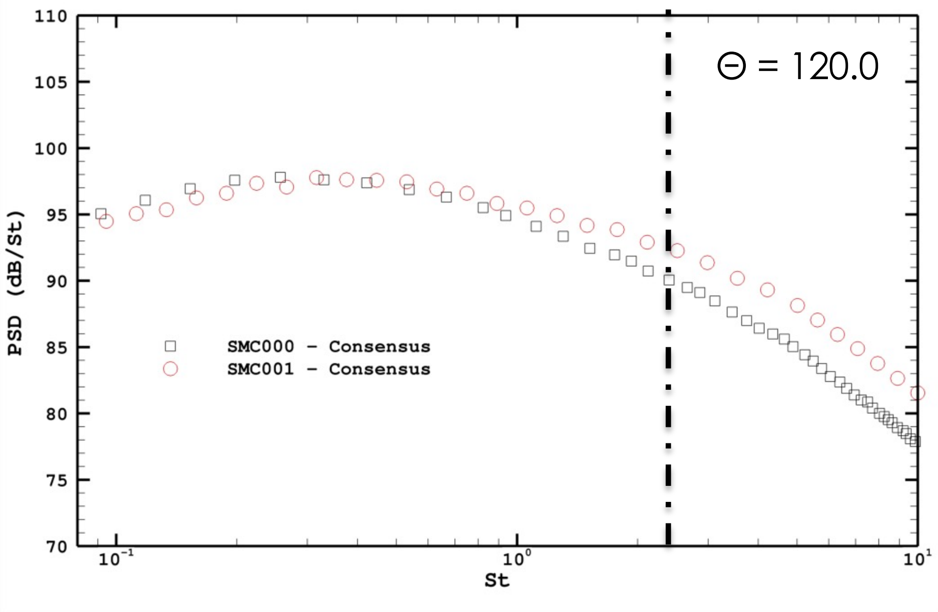


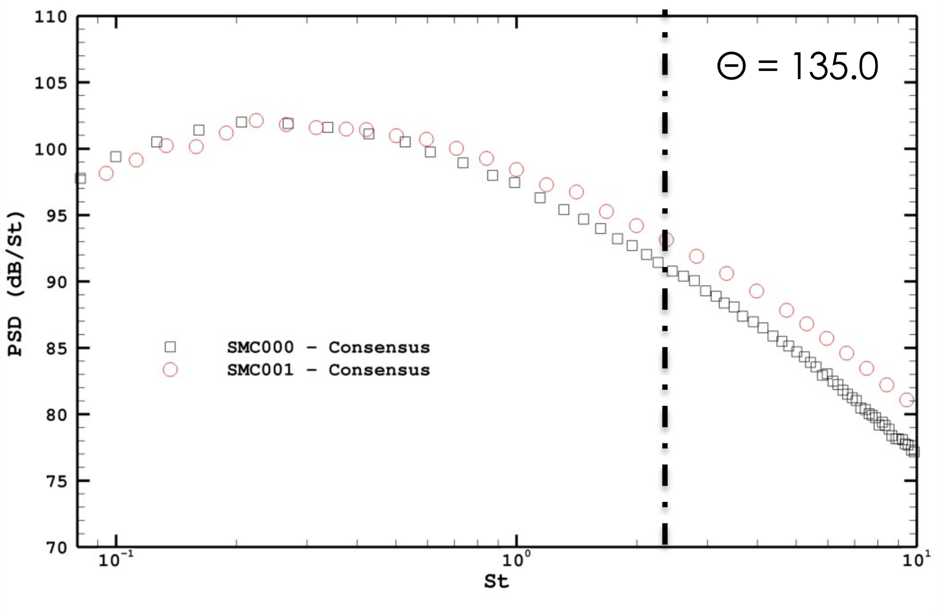
- Average over 72 azimuthal observers per microphone
- Interpolate volume solution at Sampling Frequency 200,000Hz
- Samples taken over last 600 convective time units ($\Delta t\, c_\infty/D$)
- 10 sample bins with 50% overlap
- Hanning window applied

Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron



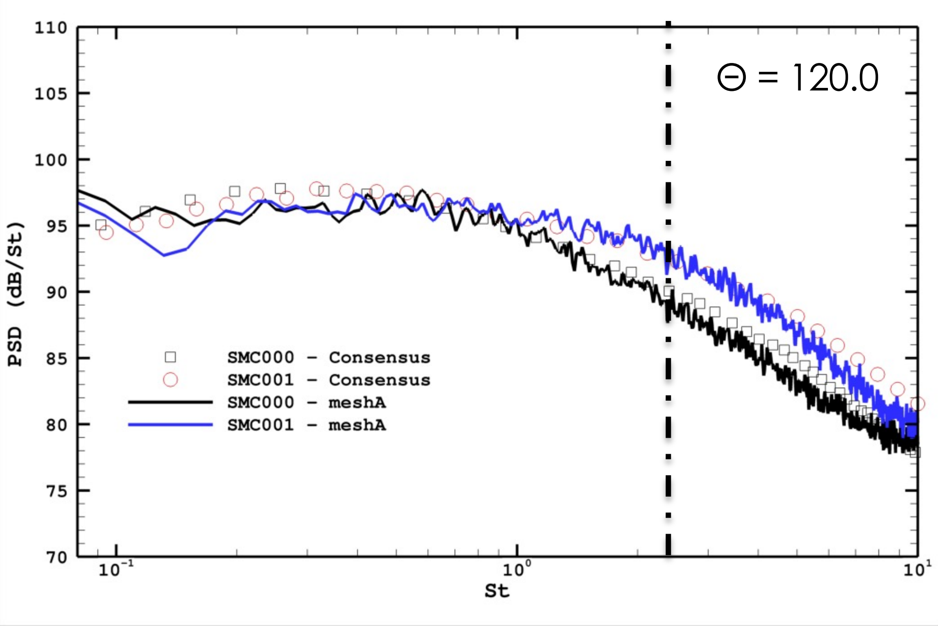


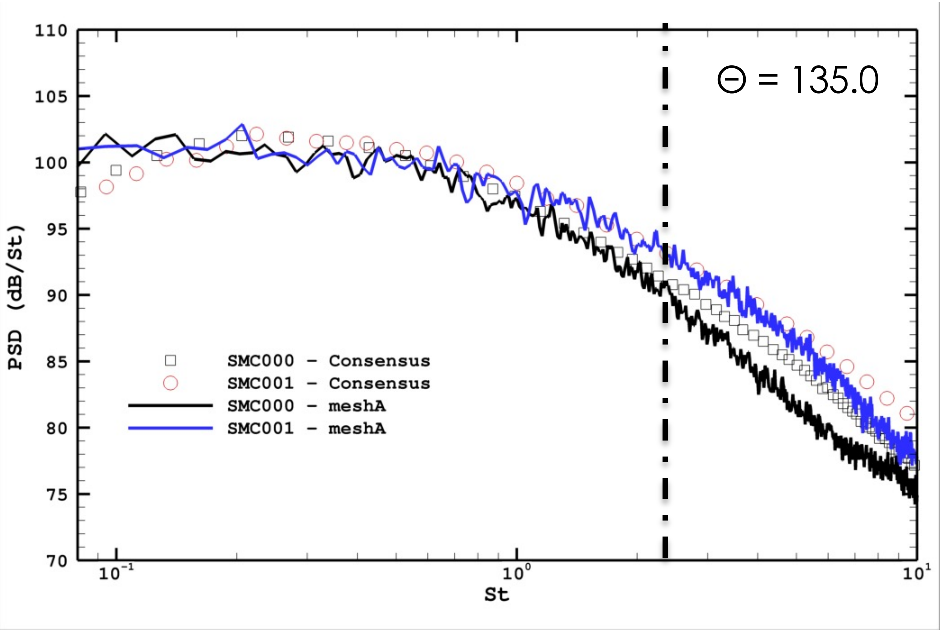


Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

- Difference between round jet and chevron for St > 1 captured in simulation
- Slight underprediction of noise at lower frequencies
- Overall good agreement with experiment





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Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets

INCREASINGLY COMPLEX GEOMETRY
(Chevron, **Plug, Multi-stream**)

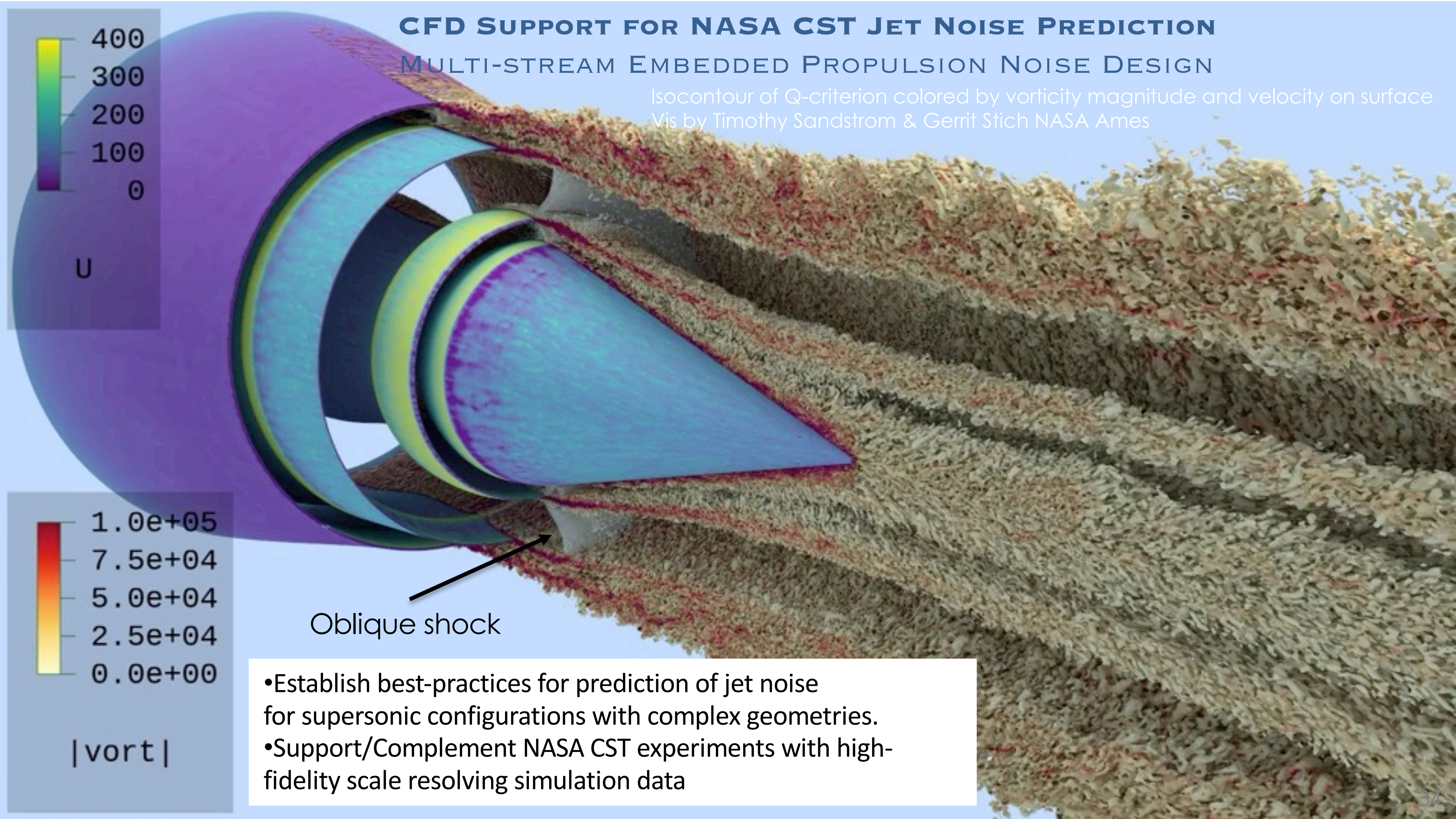
3

- **Increase geometric and numerical complexity**
- **Three-stream plug nozzle with heated primary stream**

CFD Support for NASA CST Jet Noise Prediction

Multi-stream Embedded Propulsion Noise Design

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface
Vis by Timothy Sandstrom & Gerrit Stich NASA Ames



- Establish best-practices for prediction of jet noise for supersonic configurations with complex geometries.
- Support/Complement NASA CST experiments with high-fidelity scale resolving simulation data

Timings and Code Improvements

Time savings due to algorithm, code improvements and development

Date	Method	Mesh size [10^6]	$\Delta t/c_\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
November 2019	Hybrid RANS/LES (ZDES III)	225	0.007	60 Skylake (2400 cores)	995	3.2 day / 6.5 day	--
March 2020	Wall-stress WMLES	254	0.0005	60 Skylake (2400 cores)	430	26.8 hr / 2.3 day	**2.8x**
November 2020	Wall-stress WMLES	110	0.001	60 Skylake (2400 core)	69	**4.3 hr / 8.6 hr**	**18x**
March 2022	Wall-stress WMLES	250	0.0007	100 Rome (12800 core)	106	**75min / 150 min**	**62X**

CTU: Convective Flow Through Unit

** Timings include high frequency (sampling rate 200kHz) i/o output for solution*

*** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019*

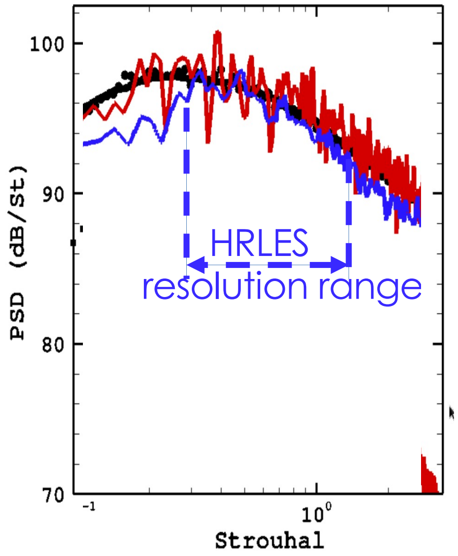
**** Improvements possible due to improved scalability of code (scales well up to 10-20k pnts/core)*

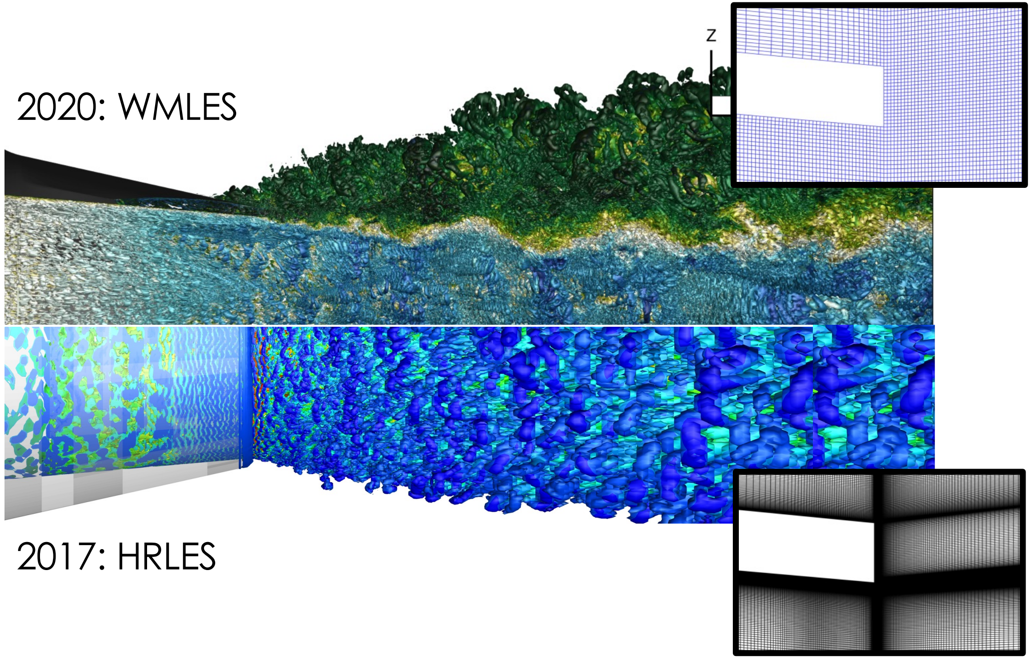
Timings and Code Improvements – Implications for Science

For the same number of mesh point we can now:

- Redistribute the same amount of points over a wider area

WMLES 2021 | Hybrid RANS/LES 2019





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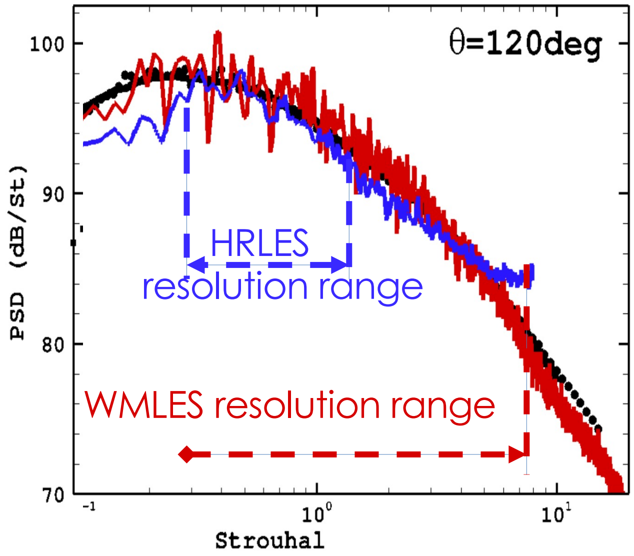
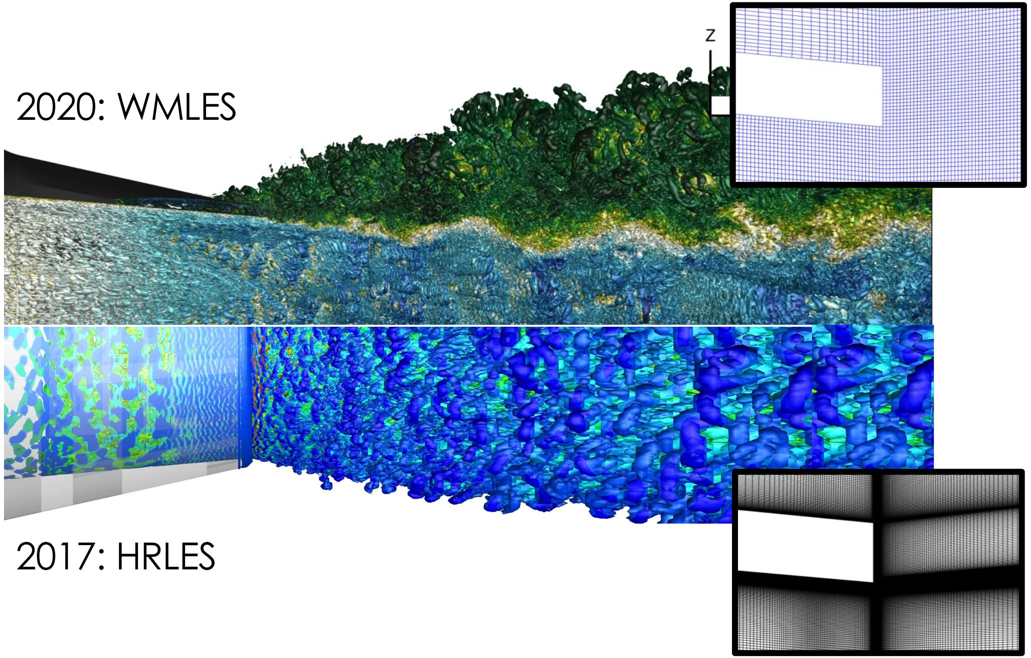


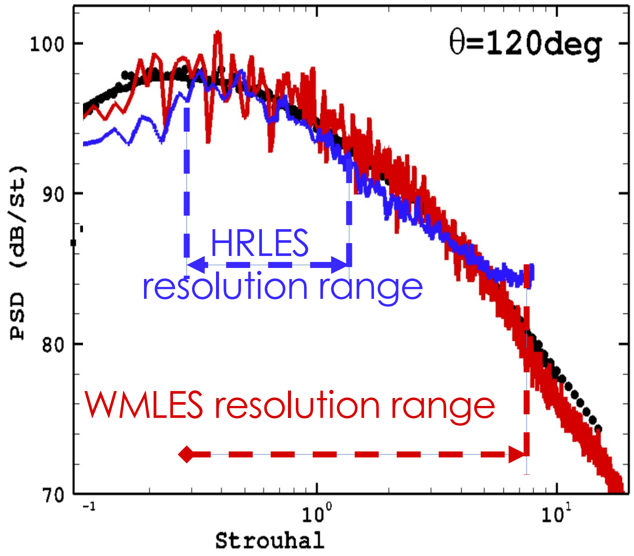


upper frequency range extended for almost a decade worth of data

Timings and Code Improvements – Implications for Science

For the same simulation time cost (CPUh) we can now:

- Increase simulation time interval



Path towards a robust, reliable and fast WMLES solver for jet noise database generation

November 2019	
Hybrid RANS/LES	6.5 days [100 Broadwell]

Today	
WMLES + Optimized Code & Best Practices & Scaling	150 minutes [100 Rome]

Timings and Code Improvements – Implications for Science

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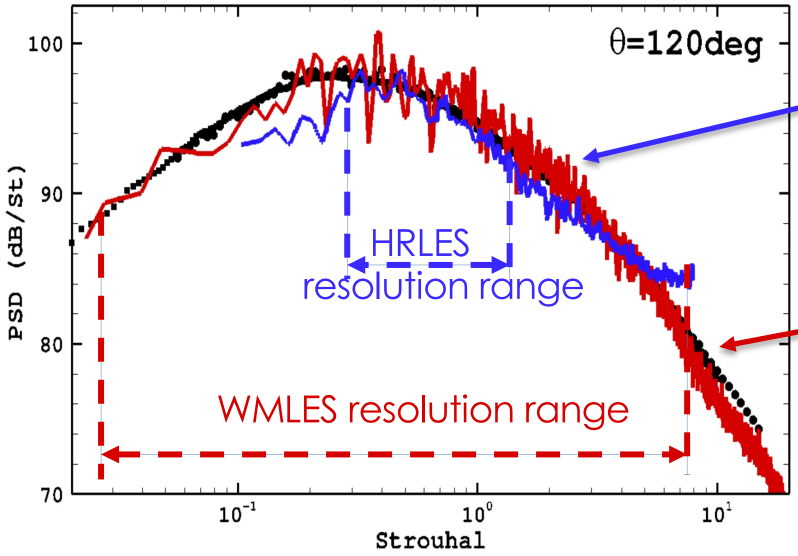


HRLES Simulation for SP7
6.5 days
60 Skylake Nodes
2,400 cores

WMLES Simulation for SP7
0.6 days
100 AMD Rome Nodes
12,800 cores

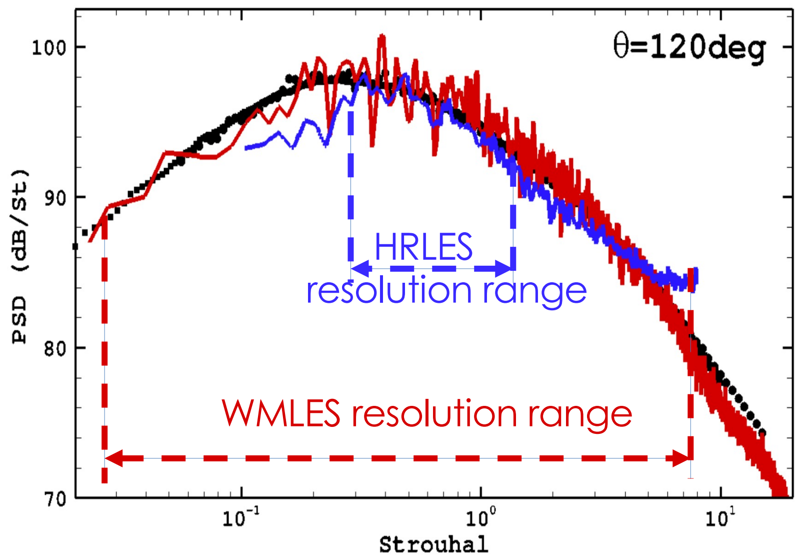
still factor of 10x faster turnaround

upper and lower frequency range extended for almost a decade worth of data

Timings and Code Improvements – Implications for Science

For the same simulation time cost (CPUh) we can now:

- Increase number of simulations in the same amount of time



SP	M_a [-]	M_{jet} [m/s]	NPR [-]	NTR [-]
3	0.5	0.51	1.197	0.96
7	0.9	0.98	1.852	0.84
23	0.50	0.38	1.102	1.76
27	0.90	0.68	1.368	1.76
29	1.33	1.00	1.898	1.76
38	1.33	0.88	1.664	2.27
46	0.90	0.56	1.219	2.70
49	1.48	0.90	1.697	2.70
101240	1.14	0.85	1.608	1.78

Code improvements enable new frontiers in WMLES for jet noise

Conclusions Part I

- ❑ Zonal HRLES methods showed improvements in transition towards shear-layer turbulence compared to classical DDES
- ❑ Step towards integrated propulsion noise with ZDES showed that the noise shielded by a plate can be captured in simulations
- ❑ Switch towards WMLES resulted in higher spatial and temporal resolution
  - More resolution for the same cost or lower costs for the same resolution
- ❑ WMLES captures the both qualitative and quantitative difference between noise generated by round nozzles and chevron nozzles
- ❑ Significant algorithmic and software improvements resulted in reduced turnaround times
- ❑ Improvements enable additional scientific explorations e.g., generation of a database to assess prediction uncertainties (Part II)

PART II
Towards Reducing Prediction Uncertainties of Jet Noise Simulations

Stich et. al. (AIAA 2022-0648)

LTO Noise Poses High Risk to Commercial Supersonic Market

Problem

- No certification noise rule for commercial supersonic aircraft
- FAA has issued a ‘Notice of Proposed Rule-Making’ (NPRM)
- Technical committee need **reliable** noise predictions to assess environmental impact against economic benefits
- More data necessary for feasibility assessment

Question

- How good is your prediction and what is the uncertainty?

April 2020: FAA issues NPRM for commercial supersonic transports

DEPARTMENT OF TRANSPORTATION

Federal Aviation Administration

14 CFR Parts 21 and 36

[Docket No.: FAA–2020–0316; Notice No. 20–06]

RIN 2120–AL29

Noise Certification of Supersonic Airplanes

AGENCY: Federal Aviation Administration (FAA), DOT.

ACTION: Notice of proposed rulemaking (NPRM).

New Technical Challenge – Prediction Uncertainty Reduction (PUR)

- Use physics-based simulations (PBS) of supersonic aircraft jet noise to produce ‘data’

More details on PUR: James Bridges – NASA Acoustic Technical Working Group Meeting, 2021

Generate aeroacoustics Database for single-stream round jet using WMLES

- Baseline axisymmetric convergent Small Metal Chevron (SMC000)

SP	M_a [-]	M_{jet} [m/s]	NPR [-]	NTR [-]
3	0.5	0.51	1.197	0.96
7	0.9	0.98	1.852	0.84
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27	0.90	0.68	1.368	1.76
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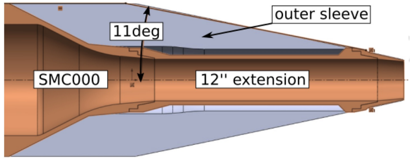
101240	1.14	0.85	1.608	1.78

colored by NTR

nozzle geometry

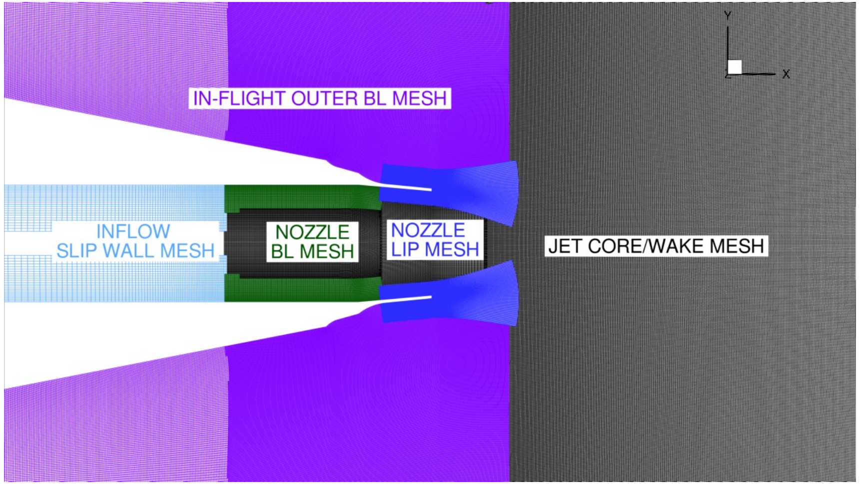
Bridges et al. (NASA-TM-2011-216807)

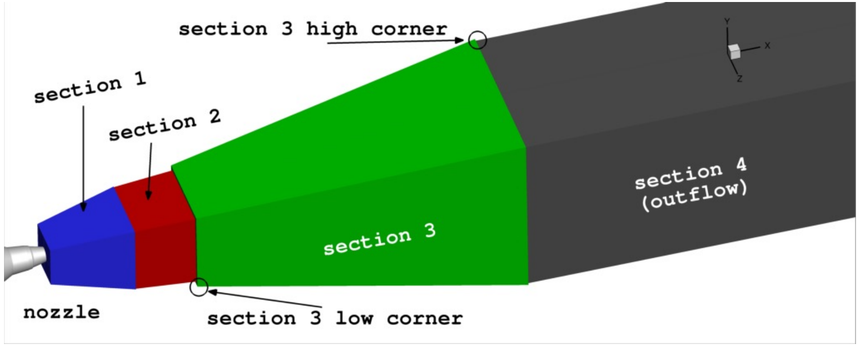


- Located at Glenn Research Center (GRC)
- Small Hot Jet Acoustic Rig (SHJAR)
- Far-field acoustics, phased arrays, flow rakes, hotwire, schlieren, PIV, IR, Rayleigh, Raman, PSP

Overset Grid System – Key Focus of Meshing

- Consistent mesh for all simulations configurations (330M) (including in-flight reference condition not part of this presentation)

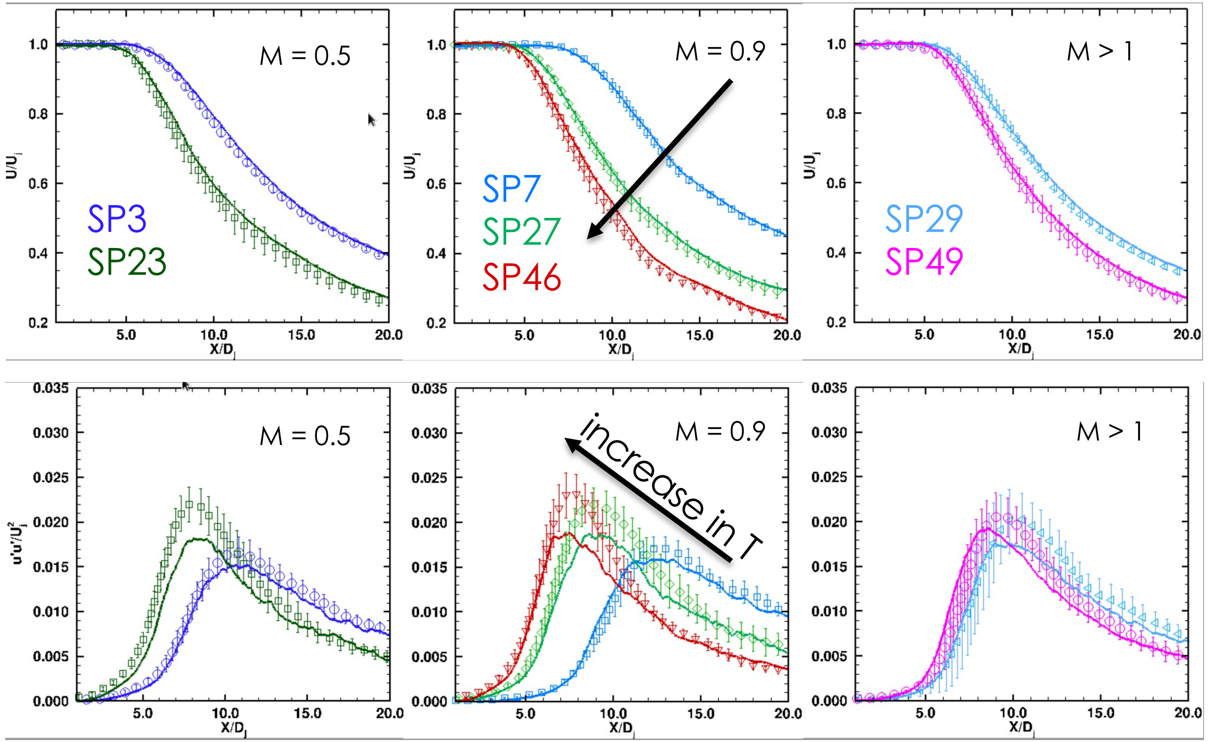




section	x_{lo}	r_{lo}	Δ_{lo}	x_{hi}	r_{hi}	Δ_{hi}
1	0.0	1.5	0.010	5.5	-2.50	0.015
2	5.5	2.5	0.015	10.0	-2.75	0.020
3	10.0	3.0	0.020	35.0	-6.00	0.040
4	35.0	6.0	0.080	70.0	-6.00	1.500

- Almost isotropic (AR=1) mesh to reduce grid anisotropy effects
- Near-wall meshes curvilinear cylindrical meshes
- Wake/core mesh cartesian like mesh

Near-Field Comparison: Centerline Velocity and Normal Stress

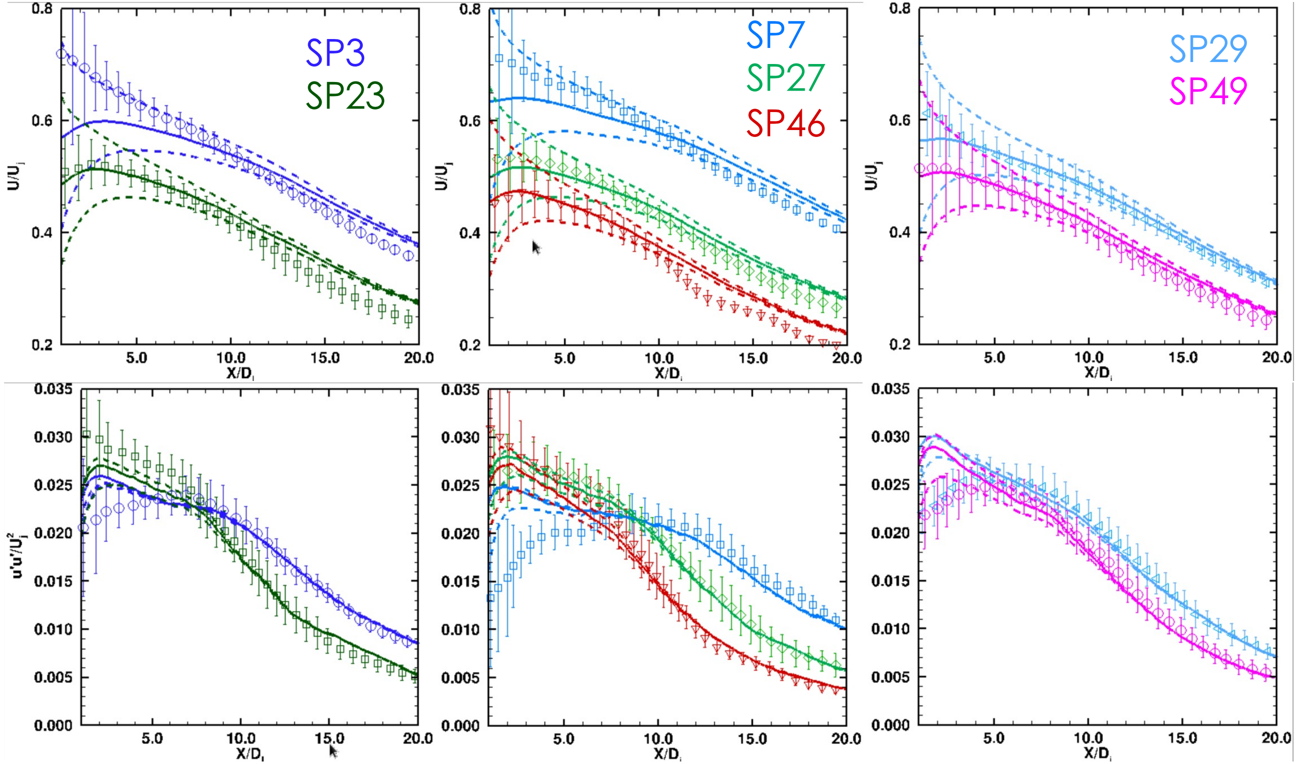


Flow Conditions

SP	M_a [-]	NTR [-]
3	0.5	0.96
7	0.9	0.84
23	0.50	1.76
27	0.90	1.76
29	1.33	1.76
46	0.90	2.70
49	1.48	2.70

- Length of potential core predicted accurately for all simulations
- Location of normal stress agrees well with experiments
- Slight under-prediction of peak magnitude normal Reynolds stress

Near-Field Comparison: Lipline Velocity and Normal Stress

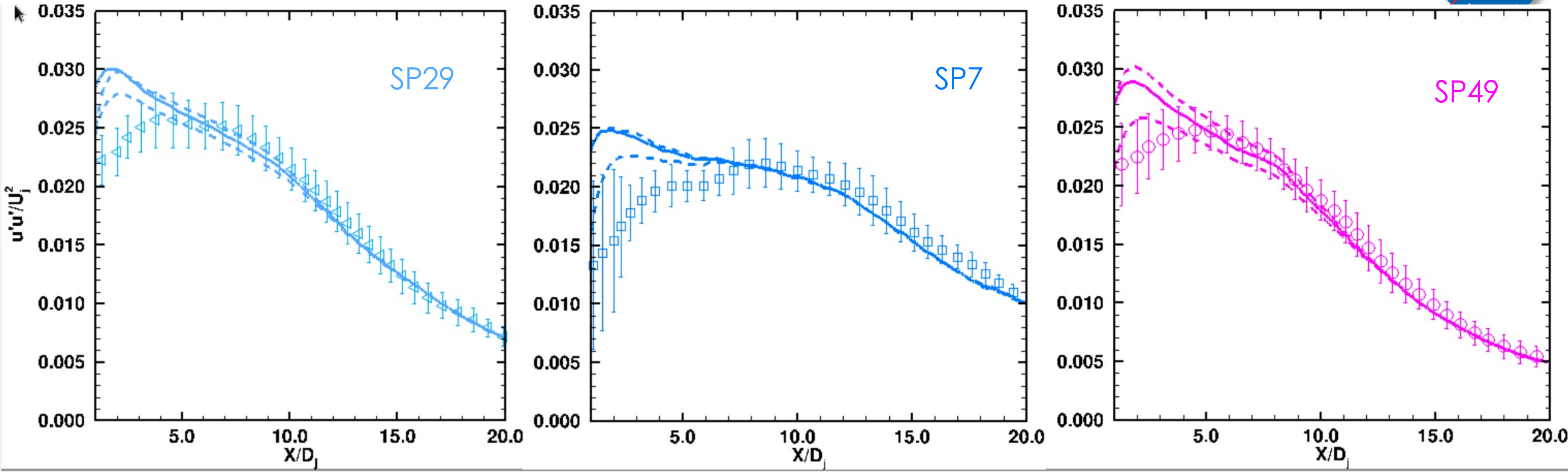


Flow Conditions

SP	M_a [-]	NTR [-]
3	0.5	0.96
7	0.9	0.84
23	0.50	1.76
27	0.90	1.76
29	1.33	1.76
46	0.90	2.70
49	1.48	2.70

- Overall good agreement with experiments for lipline velocity and normal stress
- Strong variation in values +- $0.01D_{jet}$ above and below lipline up to $10D_{jet}$ (dashed lines)

Near-Field Comparison: Lipline Normal Stress

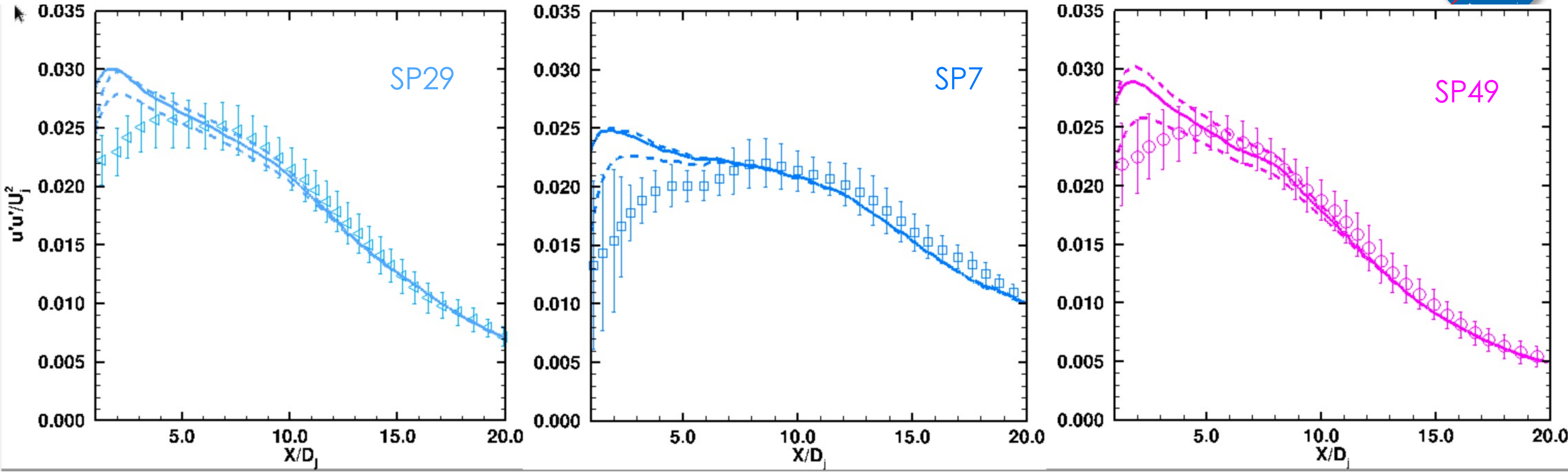


- Over-prediction of lipline normal stress up to 5D
- Correlation found between cases with jet exit Mach ≈ 1
- Potentially more resolution in shear-layer required
- Experiments at SP7 showed also large uncertainties

Flow Conditions

SP	M_a [-]	NTR [-]
7	0.9	0.84
29	1.33	1.76
49	1.48	2.70

Near-Field Comparison: Lipline Normal Stress



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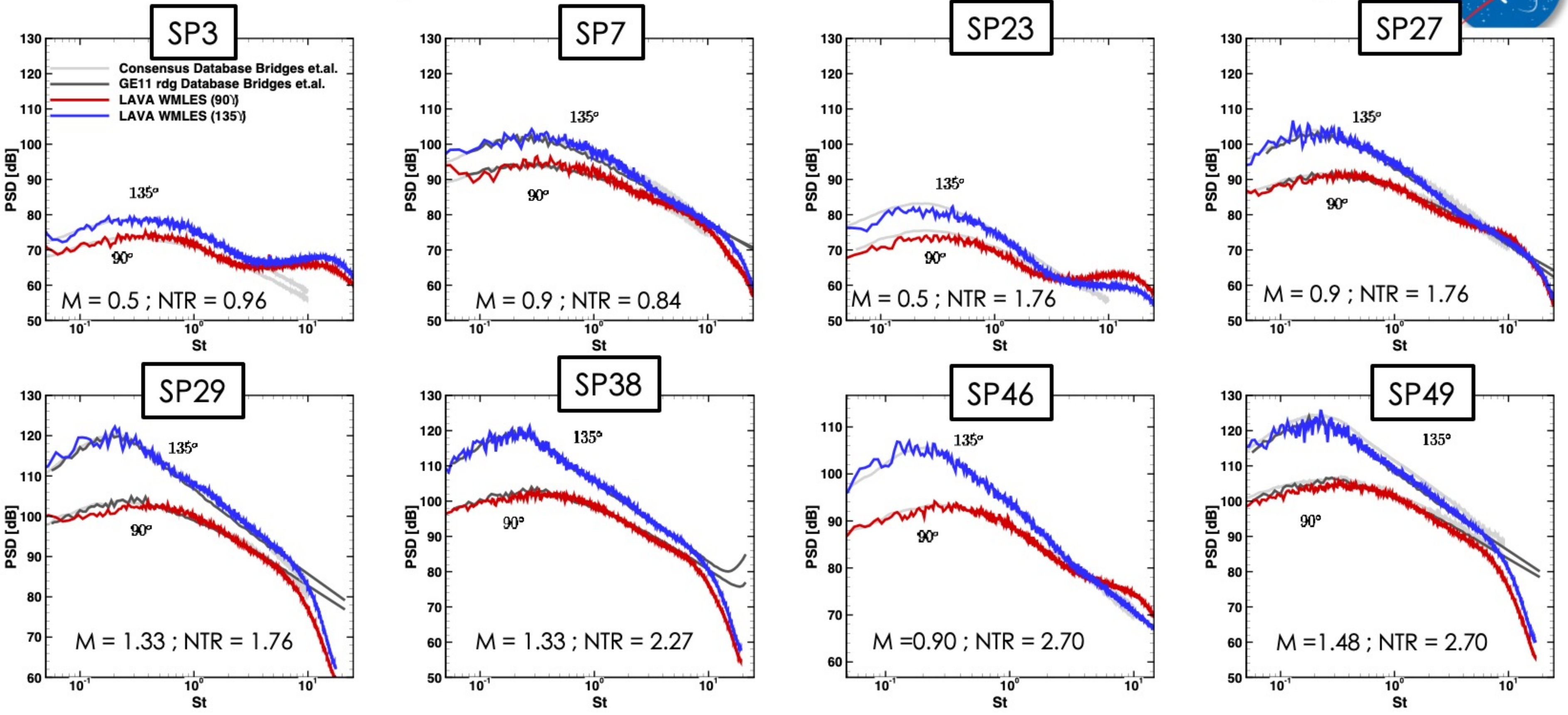
Flow Conditions

SP	M_a [-]	NTR [-]	M_{jet} [-]
7	0.9	0.84	0.98
29	1.33	1.76	1.00
49	1.48	2.70	0.95

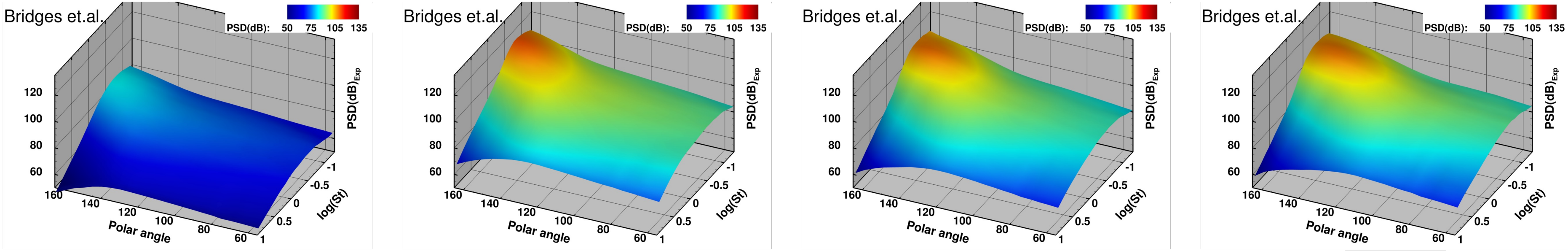
Far-field Noise Spectrum at 100D for 90deg and 135deg



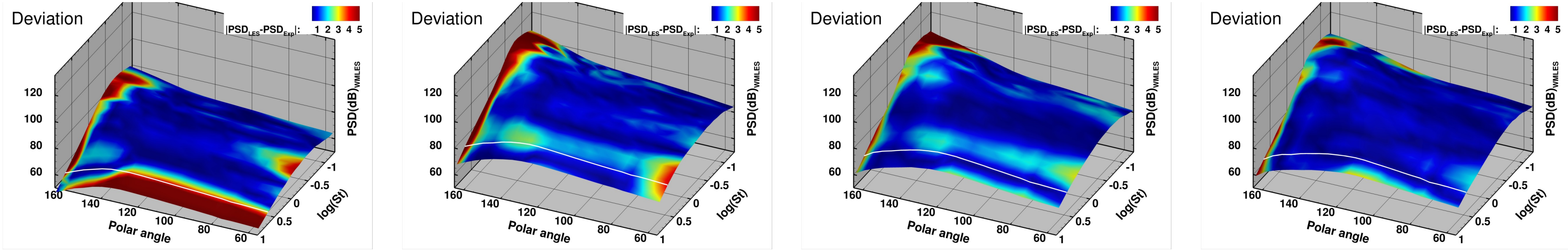
- Good agreement with microphone data until grid cutoff frequency (St_{cutoff} = 3)

Far-field Noise Spectrum at 100D: Directivity 55deg to 165deg

M = 0.5 ; NTR = 0.96 | M = 0.9 ; NTR = 0.84 | M = 0.9 ; NTR = 1.76 | M = 1.33 ; NTR = 2.27

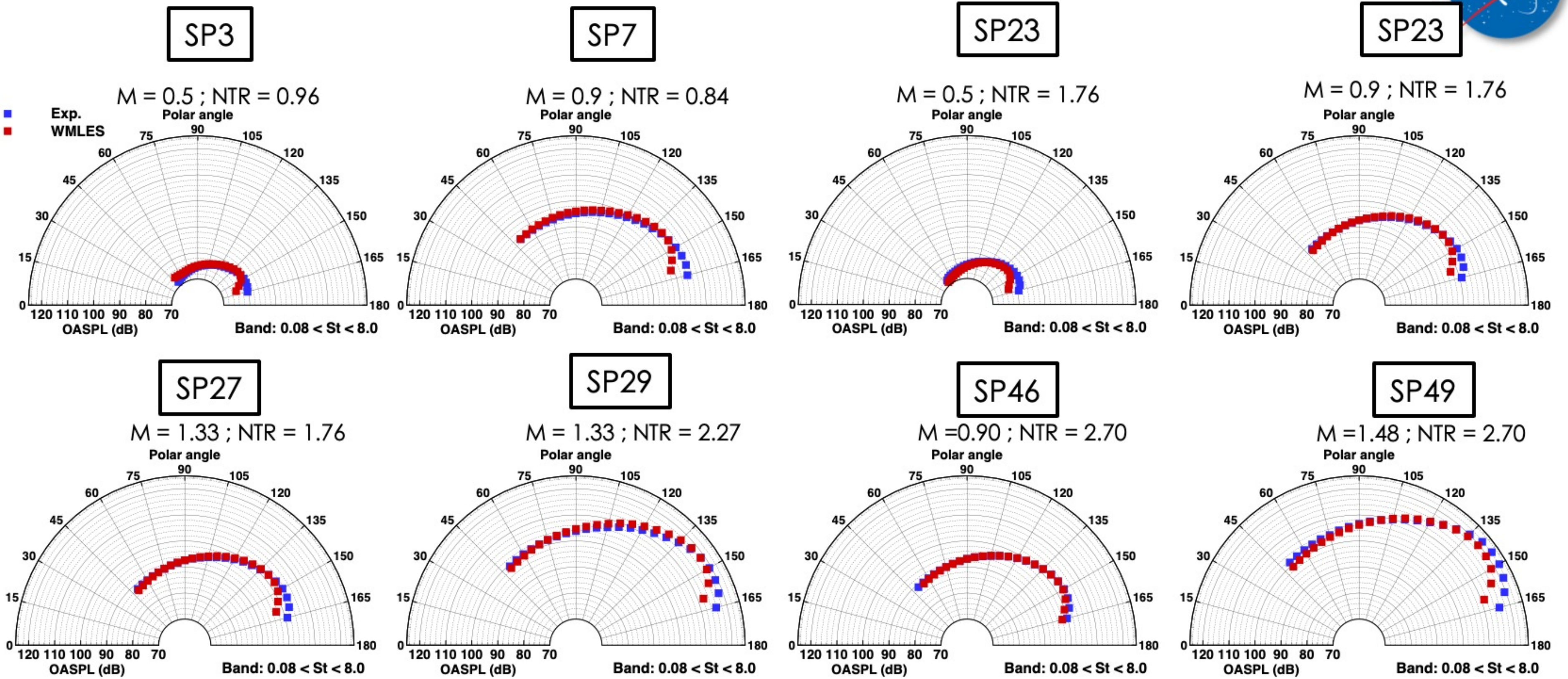


SP3 | SP7 | SP27 | SP38



- Discrepancy for far-aft angles (>150deg) and shallow angles (<60deg)

Far-field Noise Spectrum Overall Sound Pressure Level



- Consistent under-prediction of far-aft angles (>150deg) and shallow angles (<60deg)

Conclusions Part II

- WMLES database generated for static reference conditions ($M_{ref} = 0$)
- Accurate prediction of near-field quantities with PIV experimental data
  - Breakdown of potential core predicted within 1%
  - Rise of turbulent kinetic energy (TKE) along centerline predicted accurate, small under-prediction of peak TKE values
  - Overprediction of lipline TKE for SP27, SP29 and SP49
- Good comparison with far-field noise microphone array data
  - Good agreement in the resolved frequency range ($0.05 < St < 6$)
  - Under-prediction of far-aft angle larger than 150deg observed

Future Direction

The Scalability of Grid Generation

Future Directions – The Scalability in Grid Generation

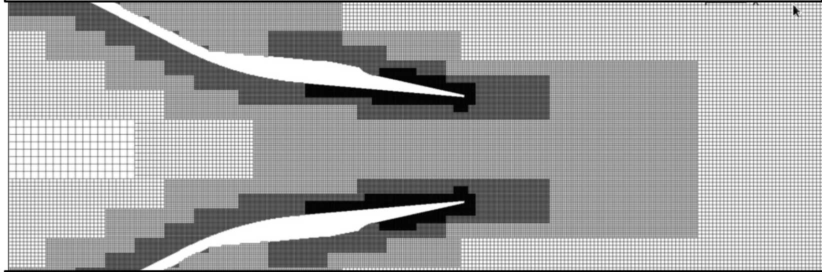
Problem:

- With increasingly complex or rapidly changing geometries meshing becomes biggest bottleneck (days to weeks)
- Curvilinear overset meshing requires subject matter expert for good results

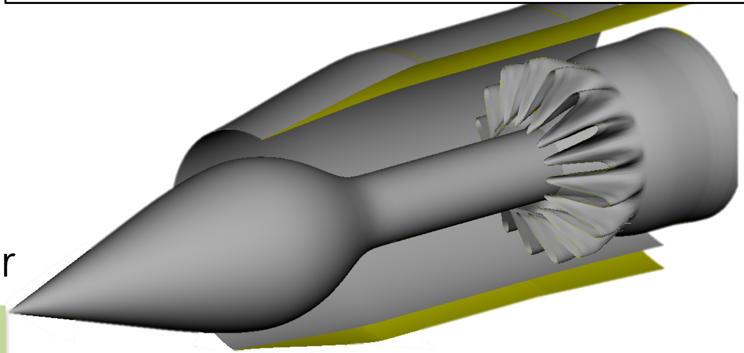
Potential Solution:

- Use of octree-immersed boundary treatment for WMLES (minutes on modern computer)
- With little instruction non-expert can make a reliable mesh
- Isotropic character of cartesian mesh has improved acoustic properties
- Algorithm is approx. 1.5-2X faster than curvilinear

cartesian octree mesh for isolated axisymmetric round jet SMC000



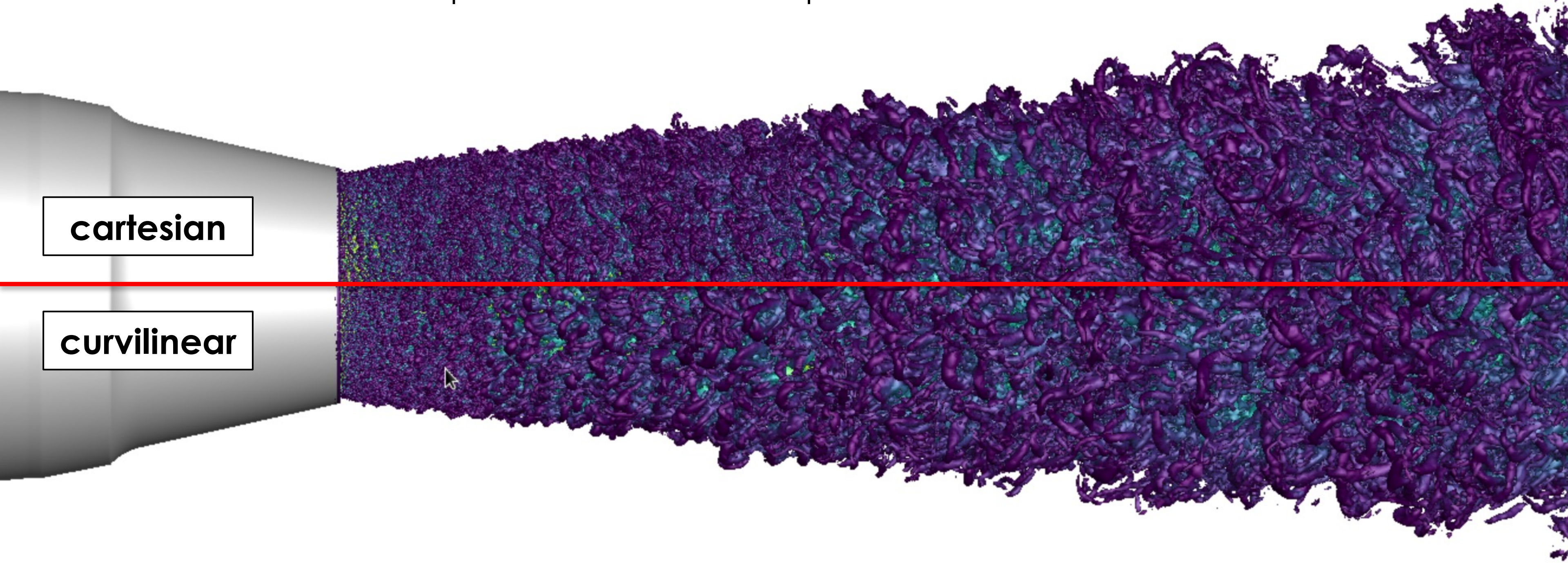
NASA plug20 nozzle with external plug and internal lobed mixer



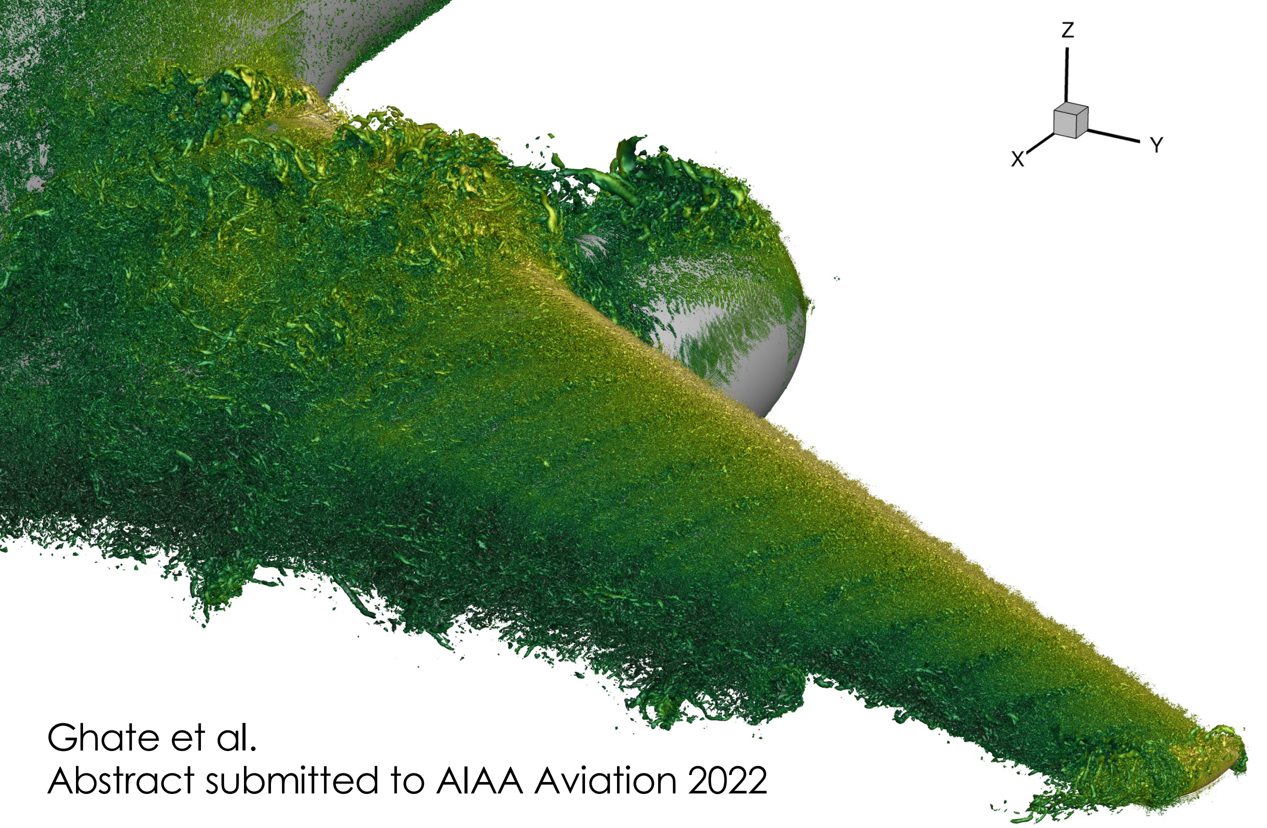
Potential increments to TRL for WMLES in jet noise

LAVA Curvilinear & Cartesian for axisymmetric round jet

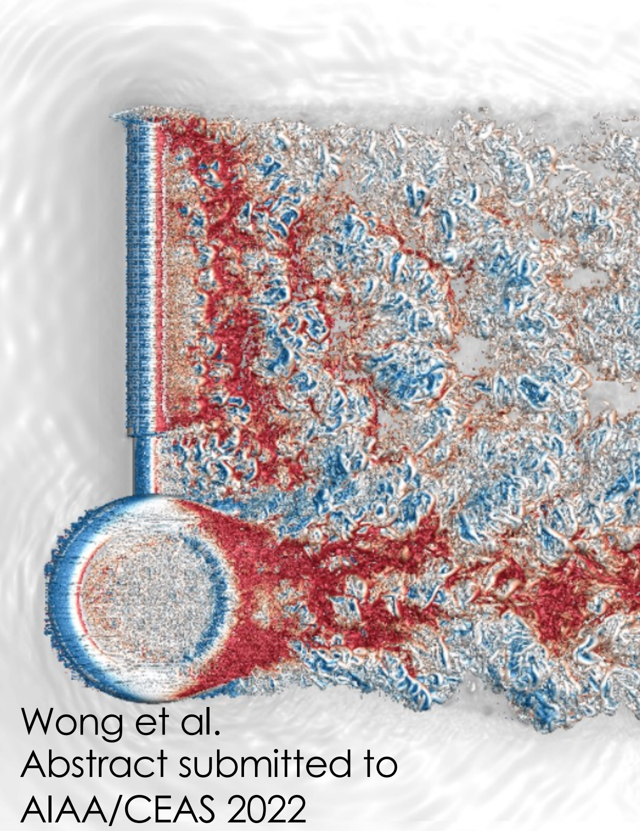
- More localized isotropic mesh refinement possible with cartesian method



Isocontour of Q-criterion colored by streamwise velocity



Ghate et al.
Abstract submitted to AIAA Aviation 2022



Wong et al.
Abstract submitted to AIAA/CEAS 2022

Cartesian Octree for Aerodynamics and Aeroacoustics within LAVA

Acknowledgments

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Questions?

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